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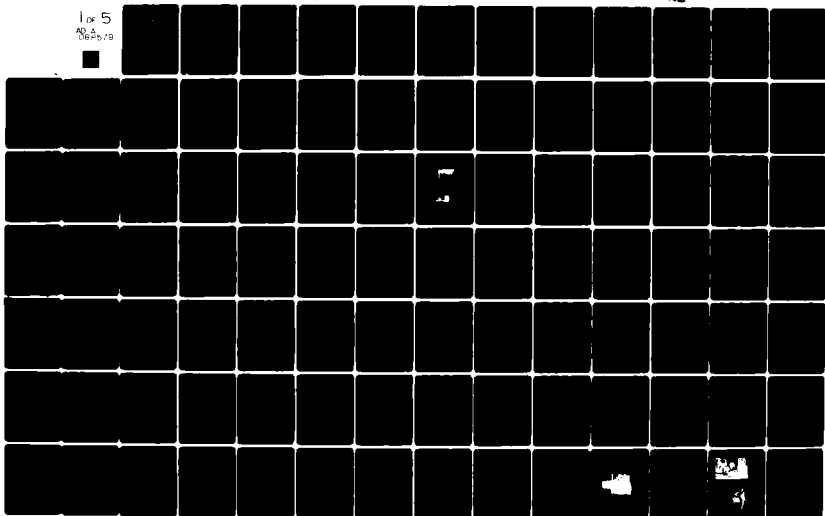
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ABSTRACTThe Development of an Accelerometer System
for Measuring Pelvic Motion During Walking

→ A planar eight accelerometer measurement system for determining the three dimensional motion of the pelvis during walking has been developed in this study. Literature reviews are given for: previous studies of pelvic motion, kinematic measurement systems and previous studies which used accelerometers to measure human locomotion activities.

Equations for the eight accelerometer configuration are derived from the general equations of rigid body motion. The method of solving these equations for angular velocity, angular position and the translational acceleration, velocity and position is developed. The design analysis for the accelerometers fabricated and used in this study and their associated electronic equipment is given. The method used to mount the accelerometers on the pelvis of subjects is presented. The equipment and method used to calibrate the system is described and this description includes the techniques used to ensure temperature stability during data collection.

→ The computer programs used to process data collected in walking tests are explained. The mathematical techniques used to integrate the equations and to filter the data are discussed. The following pelvic motion parameters are produced as functions of time: angular velocity, angular position, translational acceleration, translational velocity and translational position. The results of experimental testing of the measurement method are presented.

Graphical results for tests of seven male subjects walking barefoot, in shoes and carrying 13.6 Kg backpacks and of seven female subjects walking barefoot, in low heeled shoes and in high heeled shoes are presented. These results are compared with results from previous studies and a nonparametric statistical evaluation of the results shows that the measurement system can detect changes in pelvic motion due to different footwear and back loads.

→ It is concluded that this accelerometer measurement method can measure three dimensional pelvic motion during human locomotion activities such as walking.

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THE DEVELOPMENT OF AN ACCELEROMETER SYSTEM
FOR MEASURING PELVIC MOTION DURING WALKING

by

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Merton College

A thesis submitted for the degree
of Doctor of Philosophy.

Trinity Term 1979

University of Oxford.

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This study is dedicated to my father,
WALTER GEORGE MCMASTER
who died on the first day of Spring in 1978.
He was my best teacher and I wish that he
had lived to see this work completed.

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CHAPTER 1

INTRODUCTION AND PURPOSE OF RESEARCH

- 1.1 Introduction and Purpose of Research
- 1.2 Anatomical Description of the Pelvis and Sacrum
- 1.3 Review of Previous Studies of Pelvic Motion
- 1.4 Review of Kinematic Measurement Systems
 - 1.4.1 Photographic Systems
 - 1.4.2 Photogrammetric Systems
 - 1.4.3 Polarized Light and Photodetector Systems
 - 1.4.4 Television Systems
 - 1.4.5 Body Contact Systems
- 1.5 Review of Previous Studies using Accelerometers

1.1 Introduction and Purpose of Research

The majority of the patients referred to orthopaedic hospitals for treatment have some disorder of the lower limbs, pelvis or lumbar spine. These patients usually modify their gait to compensate for the disorder and the degree to which they deviate from "normal" walking is primarily a function of the disorder. The pelvis and sacrum form a crucial junction between the lower limbs and the lumbar spine. Forces are transmitted through the pelvis to the lumbar spine and the motion of the pelvis is an integral part of human locomotion. Biomedical studies of the pelvis and sacrum can be classified as either kinetic, the study of the effects of forces on motion, or kinematic, the study of motion without reference to the effects of forces. Most studies have focused on the kinetics of the hip joint due to the clinical interest brought about by the total hip prosthesis. The surgical replacement of the hip joint is one of the common operations appearing on the surgical list at many orthopaedic hospitals. There is also clinical interest in the kinematics of the pelvis because treatment is intended to improve the locomotion of the patient.

Although disorders of the lower limbs result in a modification of pelvic motion to compensate for the disorder, there have been very few kinematic studies of the pelvis. Adequate kinematic studies of pelvic motion have not been performed because there seems to be no suitable measurement system available to study pelvic motion. The kinematic measurement systems used to study the relatively large movements of the lower limbs are not capable of measuring the small translations and rotations of the pelvis. Therefore, the purpose of this study was to develop a kinematic measurement system capable of:

- (1) measuring the three dimensional motion(translation and rotation) and linear accelerations of the pelvis and sacrum during activities such as walking
- (2) detecting changes in the motion and linear accelerations of the pelvis and sacrum due to lower limb or pelvic disorders.

In order to test the systems capability to accomplish the above purposes, measurements were to be made of level walking and

- (1) variation of heel height in healthy female subjects
- (2) load carrying on the back in healthy male subjects.

The reasons for selecting these purposes will now be elaborated upon.

An understanding of pelvic motion is fundamental to understanding how humans walk. In a classic article, The Major Determinants in Normal and Pathological Gait, Saunders, Inman and Eberhart(1953) suggested that there were six primary determinants of human locomotion. Three of the six are pelvic movements: pelvic rotation to the right and left about the vertical axis which reduces the vertical movements of the center of gravity of the body and thereby the energy cost of locomotion; pelvic tilt, the rotation about a horizontal axis in the coronal plane, which further reduces the vertical motion of the center of gravity and the energy cost; and lateral

displacement of the pelvis which reduces the horizontal displacement of the center of gravity to a value approximately equal to the vertical displacement. The net effect of these pelvic movements is to produce a smooth, low energy motion of the center of gravity of the body when walking. They also point out that most disorders of the joints of the lower limbs will be manifested in exaggerated motions at other levels and this will be reflected in a change from the normal pattern of pelvic motion.

In spite of the evidence that understanding pelvic motion is essential to the understanding of normal and abnormal gait, very few complete studies of pelvic motion have been undertaken. Murray, et.al.(1964) concur with this and also note that in their preliminary tests on patients with hip fusions "exaggeration of pelvic tipping was an important mechanism to compensate for the absence of motion at the hip joint." It seems very likely that other disorders will also result in an alteration of pelvic motion, yet only one complete study of pelvic motion has been found in the literature, Lamoreux(1971). The literature review conducted in this area is presented later in this chapter and supports the need for a more comprehensive study of pelvic motion.

Several studies of accelerations measured in the lumbo-sacral region have been made and are summarized in the review of studies using accelerometers contained in the final section of this chapter. However, in most of these, no attempt was made to ensure that the accelerations were measured in vertical and horizontal directions. The accelerations were simply recorded as the subjects walked and thus the natural oscillations of the pelvis changed the orientation of the accelerometers. In this study it was considered essential to resolve the accelerations along coordinate axes fixed in space in order for valid comparisons to be made.

To test the measurement system, the pelvic motion of healthy male and female subjects would be measured during level walking. Since variation of heel height and load carrying could be expected to alter pelvic motion, these two conditions were included to test the ability of the measurement system to detect changes in pelvic motion. There have been various studies of the effects of high heels, both for standing, Buehler(1932), and walking, Schwartz(1935), Mathews(1963), Gollnick(1964) and Murray(1970). None of these studies investigated the effect on accelerations at the sacrum of wearing high heels. There have been several studies on the acceleration levels at the heel, pelvis and head, Guenther(1968) or Light(1977), for various floor surfaces, running and walking and with various heel materials. Therefore, in addition to testing the measurement system, useful information would be obtained on pelvic motion and changes in acceleration levels at the pelvis due to wearing high heels. For male subjects, who do not normally wear high heels, a load carried on the back was used as the test of the measurement system.

In order to accomplish these purposes, it was necessary to select a measurement system. The various systems used to make kinematic measurements, as reported in the literature, are reviewed later in this chapter. Some of these systems were eliminated from consideration as unsuitable for measuring three dimensional motion of the pelvis, such as goniometers and other systems which only measure relative motion or motion of joints. The systems being investigated for feasibility by other researchers at the time this study was begun were eliminated due to the uncertainty involved in the development of new techniques; these included the polarized light and photodetector systems and television systems. Photographic systems have been used to obtain acceleration data in several previous studies. However, these require a great deal of manual effort to obtain results and most studies reported that accurate acceleration data

was difficult to obtain when displacements were small. This is because the double differentiation required magnifies any errors present in the displacement data. As the displacements of the pelvis are small, and accelerometers provide the data directly, the use of photographic methods was rejected. The decision to pursue the use of a three dimensional measurement system for measuring pelvic motion based on accelerometers was made after careful evaluation of the several systems available and consideration of all the needs and purposes of this study.

In the remaining sections of this chapter an anatomical description of the pelvis and sacrum and reviews of previous studies of pelvic motion, kinematic measurement systems, and previous studies using accelerometers are presented. Chapter 2 presents the theoretical analysis for the accelerometer configuration used in this study and the method of obtaining displacement and rotation data from accelerometer measurements. In chapter 3 the experimental apparatus is discussed. The chapter includes details of the design, fabrication and testing of the accelerometers and the electronic equipment required for their operation; the method used to mount the accelerometers on the sacrum of subjects; and the equipment used to calibrate the accelerometers prior to data collection. In chapter 4 the method of acquiring and processing data from subjects is explained. This includes calibration procedures, subject preparation, and walking test sequences and a description of the computer programs used to store and process test data. Also included in this chapter are estimates of experimental errors based on tests of the accuracy of the system. Chapter 5 presents the results of the walking tests on subjects. A discussion of these results is contained in chapter 6 and conclusions and recommendations for future studies are presented in chapter 7.

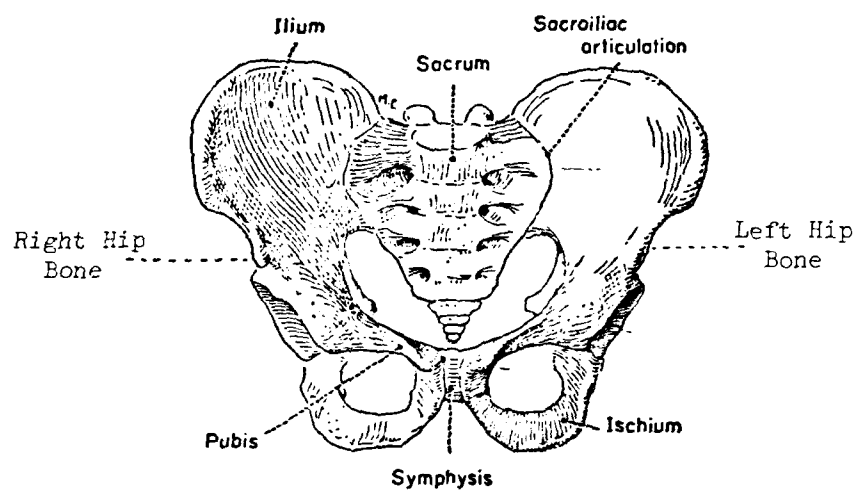


Figure 1-1. The Pelvic Ring
(from Wells)

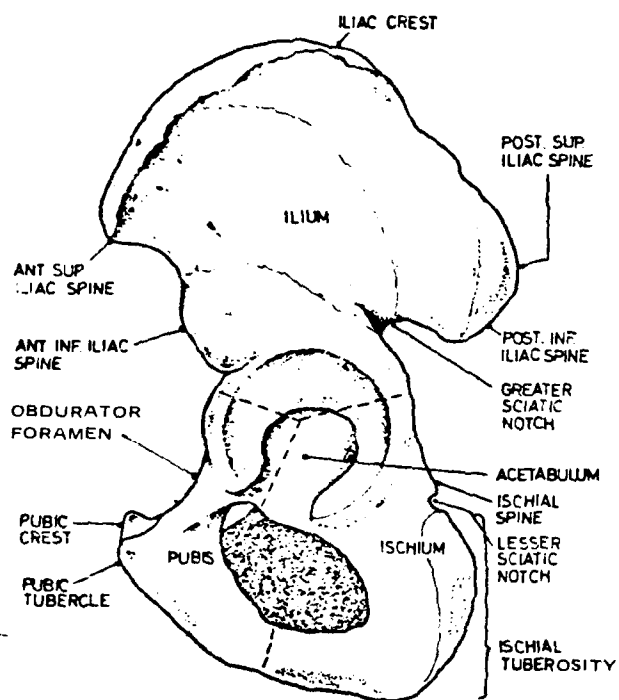


Figure 1-2. The Hip Bone
(adapted from Passmore & Robinson)

1.2 Anatomical Description of the Pelvis and Sacrum

Any study of the human body, or any of its various segments, requires a knowledge of the structure of the component members of that segment. Therefore a brief anatomical description of the bony structure of the pelvis and sacrum, the pelvic ring, will be presented in this section. As this study involves measuring the motion of the pelvis during walking a coordinate system must be established as a reference frame in which measurements can taken. The coordinate system which was used in this study will also be described in this section.

The pelvic ring, as shown in Figure 1-1, serves to transmit forces from the lower limbs to the vertebral column, via the hip and lumbosacral joints, and to provide support to the abdominal viscera from below. In adults it is composed of three bony structures: two hip bones and the sacrum which is a solid section of bone formed by the fusion of the five sacral vertebrae. There are two interior joints, the pubic symphysis and the sacroiliac joint, and three exterior joints, the two hip joints and the lumbosacral joint. The pelvic ring resembles a large funnel and is very different in the two sexes. The female pelvis is much broader and shorter than the male pelvis. In addition, the brim of the pelvic ring has a larger diameter in the female.

During childhood, the hip bone, shown in Figure 1-2, consists of three bones, the ilium, ischium and pubis; these bones fuse into one solid bony structure in the adult. The largest of these is the ilium which is a large flat bone ending superiorly in the iliac crest. The prominences at either end of the iliac crest, both of which are easily palpated through the skin and muscle tissue, are the anterior superior iliac spine and the posterior superior iliac spine. Below these lie the anterior and posterior inferior iliac spines which are very difficult to palpate. The lower end of the ilium terminates in the upper portion of the acetabulum, the socket

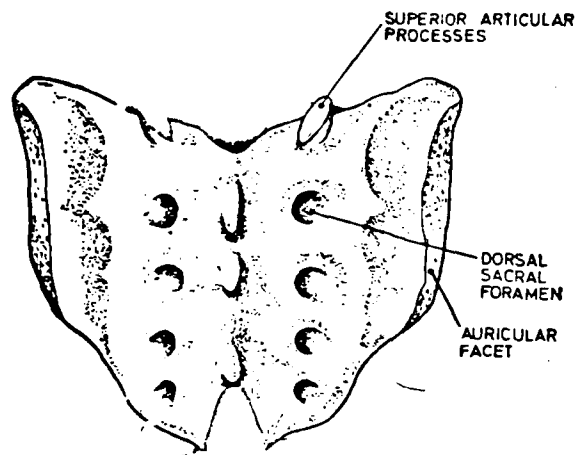


Figure 1-3. Rear View of the Sacrum
(adapted from Passmore & Robinson)

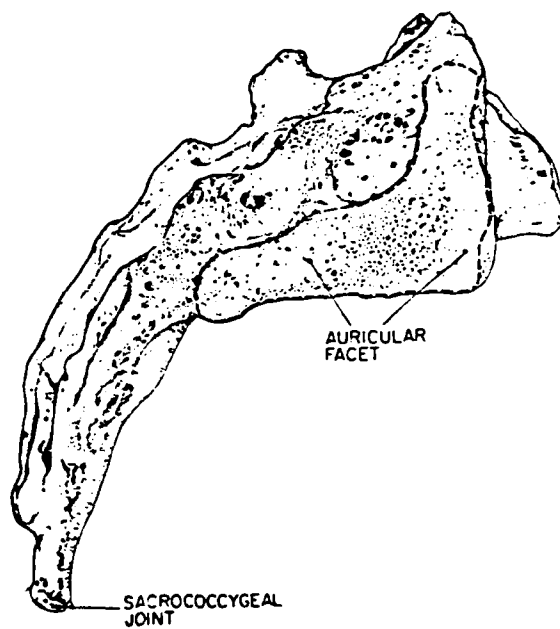


Figure 1-4. Side View of the Sacrum
(adapted from Passmore & Robinson)

of the hip joint. Between the acetabulum and the posterior inferior spine is a curved section of bone known as the greater sciatic notch.

The next largest section of the hip bone is the ischium. Its outstanding feature is the ischial tuberosity which we sit upon. Above the ischial tuberosity, the spine of the ischium protrudes medially and the margin of the ischium forms the lesser sciatic notch. Ischial bone also forms a section of the lower portion of the acetabulum. A strong section of bone called the ramus of the ischium begins at the anterior aspect of the ischial tuberosity and unites with the corresponding section, the inferior ramus of the pubis, to form the conjoined ramus.

The inferior ramus leads to the body of the third bony section of the hip bone, the pubis. The pubis is also a flat section of bone which has a superior pelvic surface and an inferior femoral surface. The anterior section stands out as the pubic crest and at the lateral end of this crest is the pubic tubercle. The pubis also forms part of the acetabulum and its superior ramus joins the ilium at the iliopectineal eminence. A large hole, the obturator foramen, appears just below the acetabulum and is bordered by the superior ramus, the body of the pubis, the conjoined ramus and the body of the ischium.

The sacrum, shown in Figures 1-3 and 1-4, is a wedge shaped bone formed by the fusion of the five sacral vertebrae. The main bodies fuse along the midline to form the body of the sacrum while the lateral portion fuses into the lateral mass. A series of openings between the main body and the lateral mass, the anterior and posterior sacral foramina, serve as the exit points for the sacral nerves. The sacral canal is located in the center of the bone and contains the sacral nerve roots and the filum terminale. The sacrum articulates with the iliac bones to form the sacral joint.

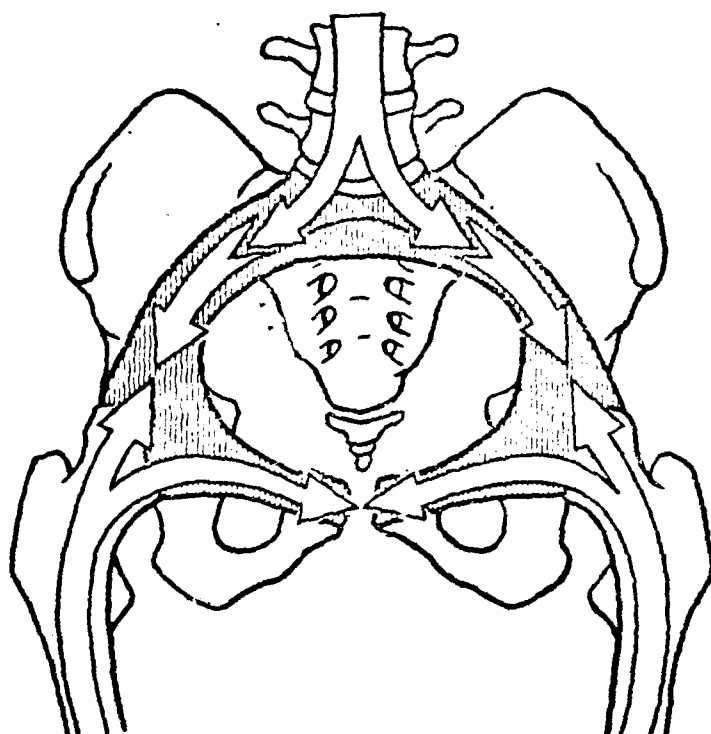


Figure 1-5. Forces in the Pelvic Ring
(adapted from Kapandji)

The sacroiliac joints are synovial joints although very little movement takes place at them, Egund, et.al.(1978). The articular surfaces are rough and irregular with the protuberances on the sacrum fitting into the depressions on the ilium. Both articular surfaces are in the shape of a crescent and are lined with cartilage. The joint is bound together with some of the strongest and shortest ligaments in the body, the primary one being the interosseus sacroiliac ligament. The short and long posterior sacroiliac ligaments, and the sacrotuberous and sacrospinous ligaments also help to provide extensive and strong ligamentous support to this joint. This extremely strong support is essential as the weight of the upper body tries to drive the anterior portion of the sacrum down between the ilia. Consequently, the posterior portion of the sacrum would "seesaw" upward if it were not for the tethering action of these ligaments which prevent the tip of the sacrum from moving away from the ischial tuberosity.

The pubic symphysis is a cartilaginous joint with a disc of fibrocartilage nesting between the right and left bones. The joint is strongly bound together by the anterior, posterior, superior and inferior ligaments. The pubic symphysis is a very strong joint and has minimal mobility except during childbirth when water is absorbed into the soft tissues allowing the female pubic bones to slide on each other and move apart.

The pelvis, or the pelvic ring, consists of three bony structures, the right and left hip bone and the sacrum, which articulate at the sacroiliac and pubic symphysis joints. It forms a strong and rigid structure whose primary function is to transmit forces from the lower limbs to the vertebral column. Within the bony structure there is a pattern of bony trabeculae which apparently correspond to these lines of force. Forces from the lower limbs are transmitted into the pelvis

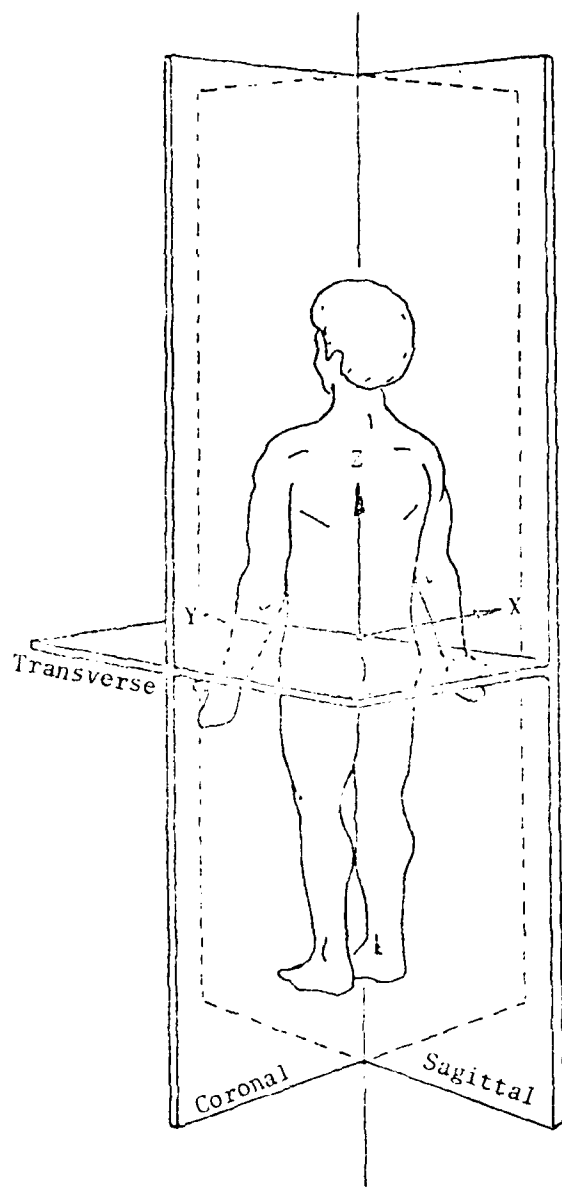


Figure 1-6. The Anatomical Planes and Coordinate Axes

through the hip joint while forces from the upper body are transmitted into the pelvis via the lumbosacral junction as shown in Figure 1-5.

In this study, the motion, rather than the forces, of the pelvis will be determined. In reviewing the literature, there appears to be no standard coordinate system nor a standard terminology for describing the translation and rotation of the pelvis in space. The following description of pelvic motion will be used throughout this study.

In Figure 1-6 the anatomical planes and coordinate axes which are fixed in the space, but move in the direction of the progression of the subject, are shown. The translational motions are measured relative to the coordinate system as:

- (1) right/left pelvic motion is positive to the right, negative to the left and is measured along the X axis
- (2) anterior/posterior pelvic motion is positive anteriorly, negative posteriorly and is measured along the Y axis
- (3) vertical pelvic motion is positive upward, negative downward and is measured along the Z axis.

Angular measurements are made using the convention: when the thumb of the right hand is placed in the positive direction of an axis with the fingers curled about the axis, the fingers indicate the direction of a positive rotation(right hand screw convention). Thus, the pelvic rotations are measured as:

- (1) sagittal pelvic rotation (some authors call this "pelvic tilt") is positive when the anterior section of the pelvis moves upward and negative when the anterior section moves downward about the X axis

- (2) coronal pelvic rotation is positive when the left side of the pelvis moves upward and negative when the right side moves upward about the Y axis
- (3) transverse pelvic rotation (some authors call this "pelvic rotation") is positive when the right side of the pelvis moves forward and negative when the left side moves forward about the Z axis.

Having described the skeletal structure of the pelvis and the coordinate system in which motion of the pelvis can be measured, a review of some of the previous studies of pelvic motion will be presented.

1.3 Review of Previous Studies of Pelvic Motion

There have been very few studies in which the motion of the pelvis was the primary focus of the study. In most cases the primary interest was in the motion of the lower limbs and only one or two of the six parameters which completely describe the translation and rotation of the pelvis were measured. Only Lamoreux(1971) reported measuring all these parameters. Therefore this review will discuss only those portions of previous studies relating to the measurement of pelvic motion.

One of the most comprehensive studies of lower limb and pelvic motion began in 1947 at the University of California at Berkeley and in 1948 Levens, et.al. reported on the transverse rotations of the lower limbs including the pelvis. The method involved the insertion of stainless steel threaded pins into bony prominences of the iliac crest of the pelvis, the adductor tubercle of the femur and the tibial tubercle. Targets, consisting of light wooden rods with spheres at two points, were attached to the pins. Subjects were then filmed while walking using three synchronized 35mm cine cameras located in front of the subject, perpendicular to the direction of walking and overhead. Data from 12 subjects were analyzed and the authors estimated the accuracy of the measurement of transverse pelvic rotation to be 2° for the middle 60 percent of the stance phase and the maximum variation, which occurred at toe off, to be $5-6^{\circ}$. The average transverse rotation was found to be 7.7° with a maximum range of 13.3° and a minimum range of 3.0° .

In 1964 Murray, et.al. reported the first in a series of studies designed to determine the ranges of normal values for parameters used to describe the act of walking. The measurements included walking cycle duration, duration of stance, duration of swing, duration of double-limb support, step and stride length, stride width, foot angle, sagittal rotation of the pelvis, hip, knee and ankle and the vertical, lateral and

forward movement of the trunk during level walking. The method used in this and subsequent studies consisted of placing reflective tape targets on the subject and then, using interrupted light from a stroboscope flashing at 20 times/sec, photographing the walking subject with a Speed Graphic camera. A mirror was placed overhead to record transverse as well as sagittal displacements. The pelvic targets consisted of a strip of reflective tape aligned horizontally over the lateral aspect of the pelvis for sagittal motion and a plastic rod strapped securely to the sacrum, using a divided leather belt, for motion in the transverse plane.

Sixty male subjects were subdivided into five age groups and each age group was further divided into tall, medium and short categories so that there were four subjects in each test group. The mean sagittal rotation of the pelvis was found to be 6° with maximum anterior tipping occurring just before heel strike and maximum posterior tipping occurring early in the single limb support phase. The average maximum transverse pelvic rotation in all sixty subjects was $10^{\circ} \pm 3.5^{\circ}$. The 20-25 year group showed the greatest rotation and the 60-65 and 30-35 year groups showed the least rotation in the transverse plane. The authors reported there were "striking differences" in transverse pelvic rotation between individual subjects and yet there was "striking reproducibility" on repeated trials of the same subject. Their conclusions reported

"The absence of pelvic rotation in some of our normal subjects suggests that this is not an obligatory element of normal gait, but rather a convenient excursion, available when walking and, perhaps, attitude demand it."

This indicates that measurements of transverse pelvic rotation can be expected to vary widely between individual subjects.

In 1966 Murray et.al. reported a second study comparing the effects on parameters previously studied of varying the walking speed. This study was conducted using 30 of the subjects from the previous study and the

same method of interrupted light photography was used to record the data. In Murray's studies free walking speed implies the subjects chose their own walking speed. The mean free walking speed was 151 ± 20 cm/sec and the mean fast walking speed was 218 ± 25 cm/sec. They reported that the sagittal pelvic rotation was unaffected by walking speed and remained 6° . The transverse pelvic rotation was $11.5^\circ \pm 3.8^\circ$ for free speed walking and $16.5^\circ \pm 6.4^\circ$ for fast speed walking. It should be noted that the mean free speed value varied 1.5° between the 1964 and 1966 studies.

In Klopsteg and Wilson(1968) some of the glass walkway study results from the University of California at Berkeley are cited which indicate that pelvic rotation in the coronal plane has an amplitude of approximately 8° . No indication of the accuracy of the measurements or a minimum or maximum value is cited. They also provide information about pelvic rotation in the transverse plane measured using surgical pins which was discussed earlier in this section.

In 1969 a study of walking patterns in healthy men was reported by Murray, et.al. In this study 64 normal men in age groups from 20 to 87 years old were studied using the same techniques previously reported. The subjects were each tested twice walking at a free speed and twice at a fast speed. The mean free walking speed was 139 ± 23 cm/sec and the mean fast walking speed was 195 ± 40 cm/sec. This study only reported transverse pelvic rotation and did not report on sagittal pelvic rotation. For this study the mean transverse pelvic rotation was $9^\circ \pm 4^\circ$ for free speed walking and $14^\circ \pm 6^\circ$ for fast speed walking. The decrease from 10° and 11.5° for free speed walking reported in their previous studies is probably due to the inclusion of the higher age groups as these studies have shown that transverse pelvic rotation decreases for normal men aged 60 years and older.

In 1970 a study of the walking patterns of normal women was reported by Murray, et.al. In addition to measuring the previously studied parameters at free and fast speed walking, this study included standing and walking measurements in low and high heels. Low heels had heights from 0.25" to 1.25" and high heels had heights from 2.75" to 3.75". The study showed that 17 subjects showed slightly greater anterior tipping in the sagittal plane and 13 subjects showed slightly greater posterior tipping of the pelvis when standing in the higher heels. When wearing low heels the mean rotation of the pelvis in the sagittal plane was 5° with a 2σ (two standard deviations) range of 4.4° to 5.6° for free speed walking and 6.8° with a 2σ range of 5.8° to 7.8° for fast speed walking. In high heels the rotation in the sagittal plane was 5° with a 2σ range of 4° to 6° for free speed walking and 4.7° with a 2σ range of 4° to 5.4° for fast speed walking. The total excursions of the pelvis in the sagittal plane were greatest when walking fast with low heel shoes. When wearing low heels the mean rotation of the pelvis in the transverse plane was 9.6° with a 2σ range of 8.8° to 10.4° for free speed walking and 12.8° with a 2σ range of 11.7° to 13.9° for fast speed walking. In high heels the transverse rotation was 10° with a 2σ range of 9.3° to 10.7° for free speed walking and 13° with a 2σ range of 11.8° to 14.2° for fast speed walking. As in men, the transverse rotation of the pelvis was mentioned as a more individualized and therefore more varied component of walking.

The first study of patients with abnormalities of the lower limbs or pelvis was reported by Murray, et.al. in 1971. The patients studied had unilateral hip pain due to either osteo-arthritis or avascular necrosis. This study reports the maximum sagittal rotation of the pelvis as $4^{\circ} \pm 0.3^{\circ}$ for normal men and a maximum of $11^{\circ} \pm 0.7^{\circ}$ for the patients. The transverse pelvic rotation is stated as $9^{\circ} \pm 0.4^{\circ}$ for normal men and $11^{\circ} \pm 0.8^{\circ}$ for patients with unilateral hip pain. Twenty six men were tested with left

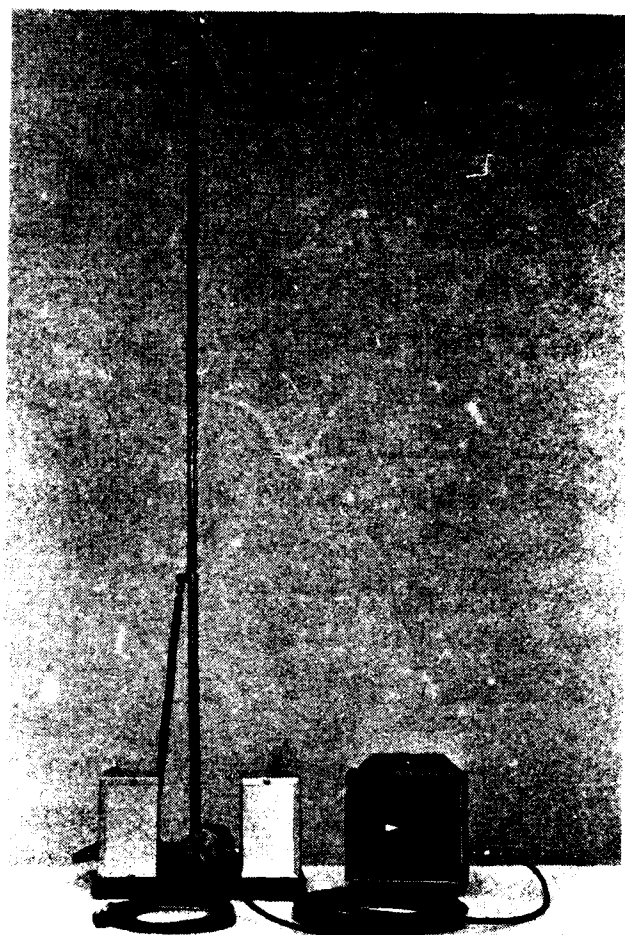


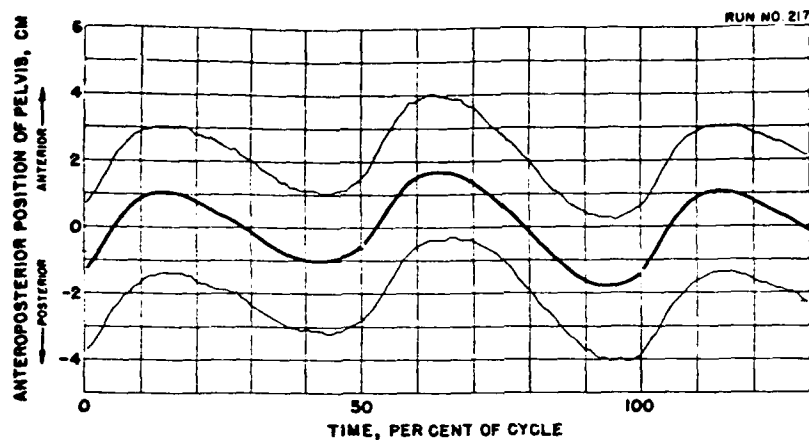
Figure 1-7. Pelvic Motion Measurement System
(from Lamoreux)

hip involvement in fifteen patients and right hip involvement in the remaining eleven. The study contains information on parameters other than pelvic rotation, but the conclusions regarding pelvic motion were:

"Increased anterior-posterior pelvic tilting, accomplished by lumbar flexion and extension, was consistently the major means of compensating for limited hip motion during walking. Anterior tilting was accentuated as the painful limb extended behind the forward-moving body, while posterior tilting motion was accentuated as the painful hip flexed forward during the swing phase. Despite this exaggerated pelvic tilting motion, the patients consistently maintained greater anterior pelvic tilting, and therefore greater lumbar lordosis, throughout the walking cycle than did normal men. Increased transverse rotation of the pelvis also served to compensate for limited hip motion, as described by Steindler."

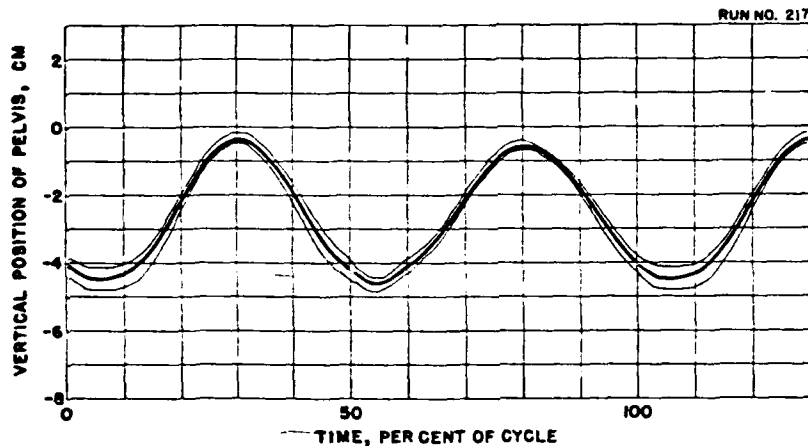
This study highlights the need for measuring pelvic motion in abnormal gait to understand the mechanisms involved in compensating for painful or abnormal joints in the lower limbs.

In 1971 the one study of pelvic motion in which all six parameters, three translational and three rotational, were measured was reported by Lamoreux. This study encompassed much more than pelvic motion, however only those parts of the study relating to pelvic motion will be discussed. The method of measuring pelvic motion consisted of having a subject walk on a treadmill while attached to three string-type potentiometer devices, one of which is shown in Figure 1-7. These devices were placed beside, behind and above the subject with the strings attached to the subject's pelvis. As the subject walks on the treadmill, the electrical signals from the potentiometers are recorded. These signals are directly proportional to the length of the strings and therefore the spatial coordinates of the pelvis. Using a computer to scale and compute the recorded signals, the translational displacements and angular rotations of the pelvis during walking were obtained. The graphic results of this study are shown in Figures 1-8 to 1-13. The rotational results of this study are comparable with the results reported by Murray, et.al. in their series of studies.



Anteroposterior (X-axis) displacement of pelvis. Measurement was made variously by a single horizontal string attached to a leather belt worn by the subject, by two parallel horizontal strings attached to a leather belt, or by two parallel strings attached to the pelvic frame. The effective point of measurement was in the sagittal plane at the level of the anterior superior iliac spines.

Figure 1-8. Anterior-Posterior Pelvic Displacement
(from Lamoreux)



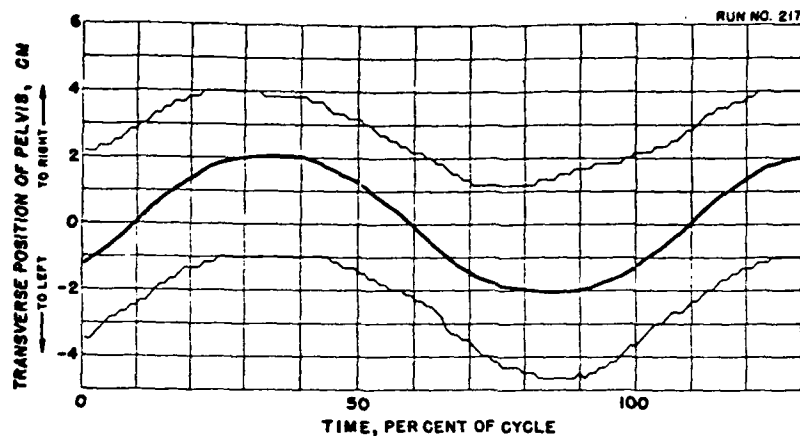
Vertical (Y-axis) displacement of pelvis. Measurement was made by means of two parallel vertical strings attached to the pelvic frame. The effective point of measurement was in the sagittal plane approximately midway between the anterior and posterior superior iliac spines.

Figure 1-9. Vertical Pelvic Displacement
(from Lamoreux)

In 1973 Waters, et.al. reported a study of translational motion of the trunk during walking. As in Lamoreux's study, cords were attached to the pelvis to measure the translation of the pelvis while the subject walked on a treadmill. The cords measuring sagittal and coronal displacement were attached to S-2 along the posterior midline. The cords measuring the transverse displacements were attached to the lateral border of the iliac crests. In a separate series of tests reported in the same article, the authors attached accelerometers to the posterior midline and recorded accelerations during walking on a level surface. Five male subjects aged 21 to 25 years were studied. The translation of the pelvis was: 4.5 cm in the transverse plane, 2.6 cm in the sagittal plane and 4.2 cm in the coronal plane. The accelerations were: 0.38 g's forward and 0.35 g's backward in the sagittal plane and 0.36 g's upward and 0.28 g's downward in the coronal plane. The translational results are comparable with those reported by Lamoreux.

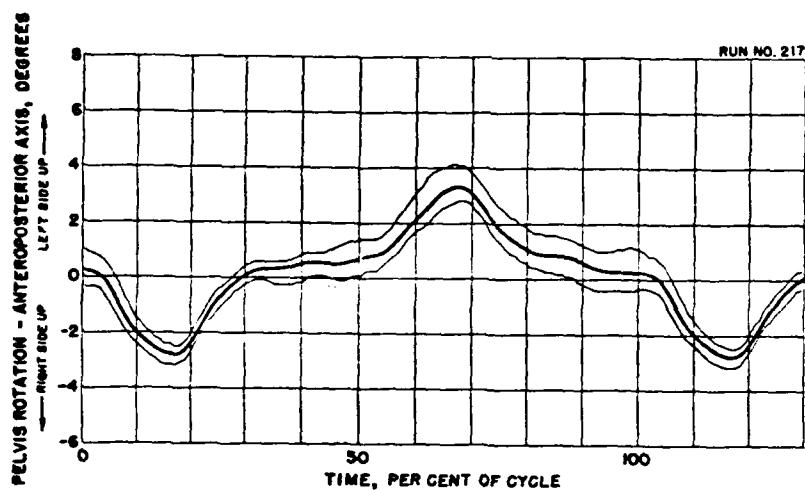
In 1975 a pamphlet was published by Mann, et.al. reporting, via graphs and charts, the results of studies at the Gait Analysis Laboratory in the Shriners Hospital for Crippled Children, San Francisco, California. No discussion of the methods used or the number of subjects studied is presented, but pelvic rotations are shown. The transverse pelvic rotation is 18° , the sagittal rotation is 2° and the coronal rotation is 9° . The transverse rotation is almost twice that reported elsewhere and the sagittal rotation is less than one-half that reported by other researchers.

The final study reviewed was conducted by Gore, Murray, et.al. and reported in 1975. The subjects were men with unilateral hip fusion and the method of measurement was the same as reported in previous studies by Murray, et.al. Twenty eight subjects were studied of which twelve had equal limb lengths, sixteen had shortened limbs on the side of the fusion



Transverse (Z-axis) displacement of pelvis. Measurement was made by means of a single string attached to the pelvic frame at the level of the anterior superior iliac spines. This string, when present, limited arm swing on the right side.

Figure 1-10. Transverse Pelvic Displacement
(from Lamoreux)



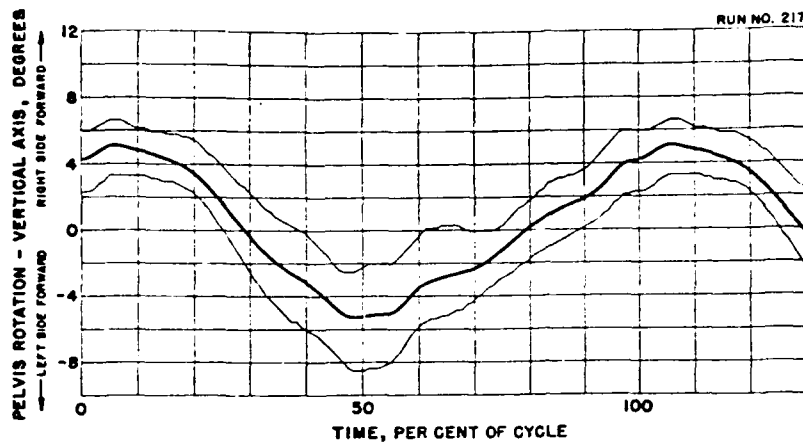
Rotation about a horizontal anteroposterior (X) axis. Attachment of the pelvic frame to the pelvis was moderately rigid about this axis. Estimated precision of the measurement: within 2 deg.

Figure 1-11. Pelvic Rotation about Anterior-Posterior Axis
(from Lamoreux)

and eleven subjects wore shoe lifts during the walking trials. The sagittal rotation of the pelvis was reported to be $15.8^{\circ} \pm 3.6^{\circ}$ for the patients compared to $7.1^{\circ} \pm 2.4^{\circ}$ for normal men. The transverse pelvic rotation also increased from $11.5^{\circ} \pm 3.8^{\circ}$ for normal men to $15.3^{\circ} \pm 4.6^{\circ}$ for these patients. Alterations in pelvic motion to compensate for lack of motion in one hip joint were stated as:

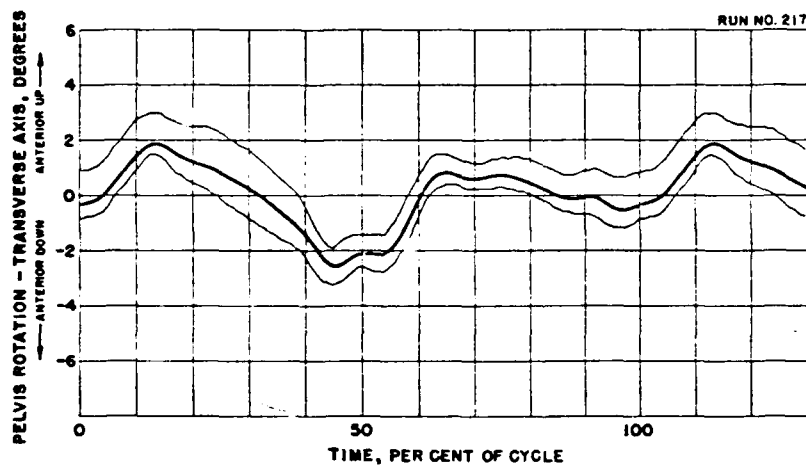
"The compensatory mechanisms that augment the excursions of the limb on the side of the fusion are excessive anterior-posterior pelvic tilt, excessive transverse rotation of the pelvis,..."

The measurement of pelvic motion and of other lower limb movements require the use of measurement systems. The various kinematic measurement systems used to measure motion of the pelvis and lower limbs will be discussed in the next section.



-Rotation about a vertical (Y) axis. Attachment of the frame to the pelvis was most rigid about this axis. Estimated precision of the measurement: within 1 deg.

Figure 1-12. Pelvic Rotation about Vertical Axis
(from Lamoreux)



-Rotation about a horizontal transverse (Z) axis. Attachment of the frame to the pelvis was least rigid about this axis. Estimated precision of the measurement: within 3 deg. The possible errors due to relative motions between pelvis and pelvic frame about this axis are considered very significant in relation to the measured displacements of the frame about the axis; the measurements and the possible error are of comparable magnitudes, and the measurements should be considered approximate only.

Figure 1-13. Pelvic Rotation about Transverse Axis
(from Lamoreux)

1.4 Review of Kinematic Measurement Systems

In order to select a method of measuring the motion of the pelvis during walking, a review of the kinematic measurement systems used by other researchers was made. Certain systems were excluded from this review because they were deemed inappropriate for this study. The use of invasive systems, such as the surgical pins used in Levens, et.al., were eliminated because they would require the assistance of a surgeon to install the pins and the general discomfort and pain they cause the subjects. Those measurement systems used in measuring forces, the kinetics of joints and limbs, were not considered as this study was concerned with the motion, or kinematics, of the pelvis. These systems include various walkways, force plates and foot switch devices.

The kinematic measurement systems will be categorized as follows: photographic, photogrammetric, polarized light and photodetector, television, and body contact systems. The discussion of these systems will not present complete and detailed explanations of each system. These details are available in either Grieve, et.al.(1975) or the articles published which report on these systems. The systems will be explained in general and some advantages and disadvantages of each will be presented.

1.4.1 Photographic Systems

The interrupted light method was introduced by Marey(1895) and is still used. This method requires placing markers on various anatomical landmarks on the subject and then photographing the subject as he walks with a single plate camera. A rotating disc placed in front of the lens produces multiple exposures on the film which are then analyzed.

Fischer(1906) and Bernstein(1934) modified the method by attaching small electric lamps to the subjects and having them walk in darkened rooms. The studies of Murray, et.al.(1964,1966,1970,1971,1975) have replaced the lights and rotating shutter with reflective tape markers illuminated by a

stroboscope which flashes at 20 times/sec.

All interrupted light systems require manual data reduction which is a time consuming process. This technique can suffer from parallax errors if the subject moves out of the specified plane of motion. It can produce very good results for movements in one plane, but overlapping movements can cause confusion. It also requires subjects to walk in a darkened room. Eberhart(1951) stated that he believed the interrupted light system was "not particularly useful in evaluation of gait", but Murray, et.al. have based many studies on this technique.

The most common photographic technique in use has been cine photography. This method was pioneered by Muybridge(1904) in his study of human movements. It was the principal method used in the University of California at Berkeley study and its use there is evaluated in Eberhart and Inman(1951). In this method markers are placed on the desired anatomical landmarks of the subject and generally two synchronized cine cameras are used to record the data. In some studies mirrors have been placed in a position for transverse plane movements, thus allowing three dimensional studies.

The use of modern lighting and cameras have greatly improved the accuracy of this method. Also, mathematical techniques for correcting parallax have been incorporated in the data reduction methods further improving the accuracy. The manual reduction of data from cine film is still the major disadvantage to this system. Attempts have been made to remove this manual labor using computer based data reduction systems as reported by Kasvand(1976) and Pepoe(1970). The systems use optical scanners or fiber optics to scan the developed film for marker location information. These systems still appear to be in the development stage.

In spite of the great amount of manual effort required to obtain data from photographic systems, they have played an important role in locomotion studies and continue to be used. However, the number of subjects which can be studied and the number of tests which can be carried out is limited by the labor available for data reduction. If fully automated methods for data reduction can be developed, these systems still will not provide immediately available data for analysis as the film must be processed and the cost of film and film processing can be appreciable.

1.4.2 Photogrammetric Systems

Photogrammetry, or stereophotogrammetry, has been used in surveying to obtain very accurate location measurements. The technique involves taking simultaneous photographs of an object in space. If the base distance separating the two cameras and the focal length of the lens of each camera are known, then the third dimension can be derived from the two planar measurements. This is accomplished by placing the negatives in a stereocomparator and, after properly calibrating the device, reading the three dimensional coordinates of the object from the projected image. To obtain accurate results very sharply defined photographic images must be used and in movement studies this may prove difficult as movement tends to blur the images. Ayoub(1970) used this technique to study hand and arm movements and claimed to measure these movements to an accuracy of 2%. A study of a seated operator moving a foot pedal by Bullock(1974) also used photogrammetry to obtain data and an accuracy of 2% was claimed for movement rates up to 30 cm/sec.

As with photographic methods, the manual labor involved in data acquisition is considerable. There is some reduction as the method involves obtaining all spatial coordinates from only one image instead of the two or three images used in interrupted light or cine film systems. Although very accurate three-dimensional position data can be obtained,

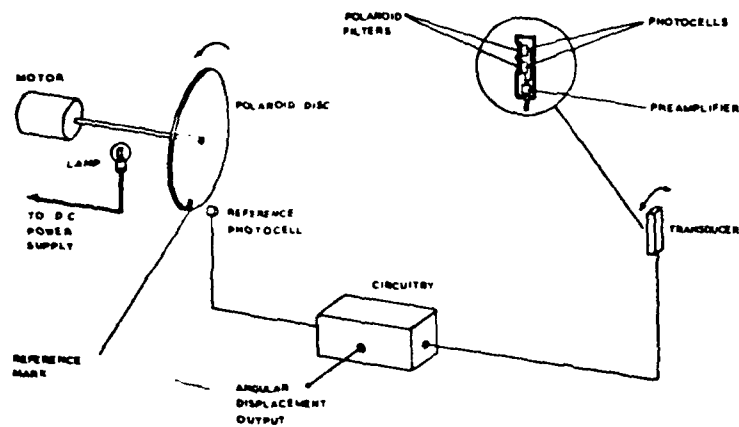


Figure 1-14. Polarized Light Goniometer
(from Mitchelson)

the cameras must be precisely aligned and this is normally a time consuming task requiring the use of precision surveying equipment. The stereocomparator is also a very costly piece of equipment and the expense involved may not be justified for the results which are obtained by this technique.

1.4.3 Polarized Light and Photodetector Systems

The general method using polarized light to measure movement was reported almost simultaneously by Grieve(1969) and Reed and Reynolds(1969). Additional research has been carried on by Mitchelson(1975) at the University of Loughborough to refine this technique. A diagram of the University of Loughborough system is shown in Figure 1-14 and the discussion will describe this system which is similar to the methods used in all the systems.

Polarized light is generated by passing light from a DC powered light source through a polaroid disc so that twice every revolution the plane of polarization is rotated through 180° . The transducers, placed at selected anatomical landmarks on the subject, consist of a matched pair of photodiodes connected in opposition to each other and covered by polaroid filters. The filters are positioned such that the planes of polarization are at right angles to each other. Thus any non-polarized light received by the photodiodes is equal in intensity and the output signal from the pair is nil. Polarized light emitted by the rotating source is received by one cell and extinguished at the other in an alternating fashion and produces a sinusoidal output voltage. A reference photocell is used to detect a reference mark on the rotating disc and produce a voltage pulse each time the mark passes the photocell.

The electronic circuitry has been designed to initiate a linear voltage ramp when the reference pulse is detected. This ramp is halted when the sinusoidal signal from the photodiode transducer passes through

zero in a negative going sense. This voltage ramp value is then stored, in a sample and hold circuit, and represents the angular displacement of the transducer with respect to the light source. This output voltage is updated at every revolution of the disc, in this system 150 times/sec. Mitchelson reported a noise level of 0.17% and the linearity as $\pm 0.1^\circ$ in a total range of 180° . In addition to angular displacement, angular velocity can be obtained by including additional sample and hold and difference amplifier circuits. This technique is a relatively inexpensive method for obtaining the relative angular position of two body segments, however it cannot measure absolute rotations or positions of a single body segment. Also, the receivers must be attached to the body and a power source for these must be carried. This system has served to popularize angle-angle diagrams as a technique for analyzing lower limb motion.

A commercial system, SELSPOT, has been developed using a continuous light spot position sensor to measure the two dimensional coordinates of a light source, Lindholm(1974) and Selcom(1975). A large area silicon photo diode sensor has been manufactured by United Detector Technology Inc. in both single axis and dual axis versions. The sensor produces analog signals which correspond to the light spot image position on the sensor surface. Light emitting diodes(LED's) are placed over anatomical locations on the subject to provide the light source which is detected by the sensor. The LED's are switched on to provide a short pulse of light and special noise suppressing and linearizing circuits are used to produce the x, y coordinates of the LED. To monitor more than one LED, time division multiplexing is required and by using two sensors three dimensional measurements can be obtained. The accuracy of the system is largely dependent on the signal to noise ratio in the sensor and signal processor, but is also a function of the incident power from the LED's. If the incident power is on the order of 1 mW a resolution of one part in ten

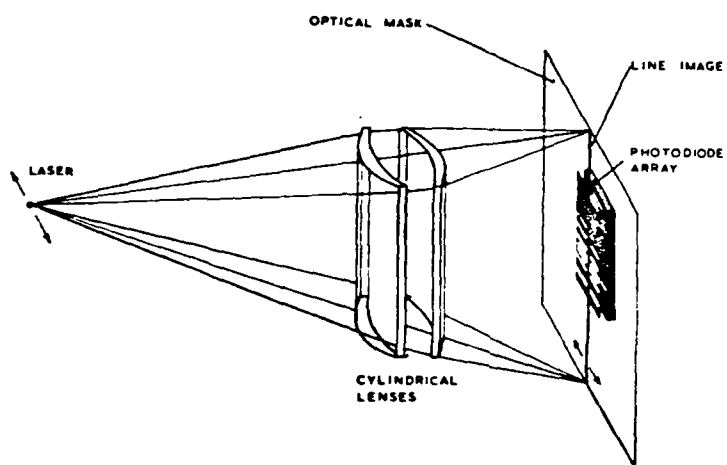


Figure 1-15. CODA Optical System
(from Grieve)

thousand is quoted. For the distances involved in most locomotion studies, currently available LED's cannot produce this power. However, Selcom has obtained resolution of 10^{-4} at a range of 6 m within a cube of 3 m sides using 30 LED's and sampling at a frequency of 200 Hz. One advantage of SELSPOT is the output of independent signals for each marker which eliminates confusion between adjacent markers which can occur in other systems. The system does require a power source and switching circuits to operate the LED's and some difficulty in attaching the markers to anatomical landmarks can be encountered if it is necessary to strap the markers to the subject.

Another system based on photo detectors is being developed by Mitchelson(1975). The system, CODA(Cartesian Optoelectronic Dynamic Anthropometer), uses an encoded optical mask which is placed in front of an array of silicon photodetectors. Point sources of light are focused by cylindrical optics into a line image on this array as shown in Figure 1-15. Any movement of the point source at right angles to the orientation of the line image causes the line image to shift across the focal plane. The photodetectors behind the optical mask are arranged to give a direct digital readout of the line image, and thus point source, position. Additional accuracy has been achieved through the use of an analog vernier and rows of transparent wedges in the mask. The final resolution is designed to be 1 part in 4096.

By using three cameras, three dimensional position data can be obtained. Two cameras, separated by a known distance, measure the two horizontal position coordinates using stereophotographic principles and the third camera measures vertical position. Laser LED's will be used as light source markers in this system to provide greater illumination power at the detector and should show better resolution than the SELSPOT system. Precise alignment of the cameras and the optical lens and mask will be

necessary to achieve the desired accuracy. The resolution will also be affected by the power and angle of radiation of the light sources.

Mitchelson plans to have the power supply for the LED's and a short range radio receiver carried in a belt pack on the subject. The receiver will synchronize the light pulses from signals transmitted from the camera control console. The subject will then be free to move about without any trailing wires to hinder his movements. This freedom of movement and the high precision of measurement possible are the major advantages of this system.

1.4.4 Television Systems

Television systems for measurement of movement have been independently developed at the University of Manitoba by Winter, et.al.(1974a,b), the University of Strathclyde by Jarrett(1976) and other locations. The primary motivation in the development of these systems has been to reduce the manual labor involved in obtaining spatial position information. The systems are based on the principle that two dimensional position information of a point located in the field of view of the television camera can be obtained by determining which raster line(vertical) the point is on and where the point is located(horizontal) on a particular raster line. The point must have sufficient contrast to be clearly visible, in these systems visibility being defined as a voltage level clearly discernible from other voltage levels exciting the television screen.

The method used at the University of Manitoba consists of following the subject with a television camera mounted on a cart and recording the output on a TV recorder. The tape is then replayed on a video recorder with an interface to convert the data to digital form for storage on a computer. Computer programs then reduce the data, calculate the absolute coordinates of the center of the markers, make the necessary corrections

for parallax and output the results. The data conversion is accomplished in the same amount of time that was required to record the data (ie. 7 seconds of gait data is converted and output in 7 seconds). This represents a major reduction in time and effort from cine or other photographic methods. The major source of error is uncorrected parallax which occurs when the subject does not walk in a straight line and the marker is at the edge of the field of view of the camera, but the reported error is not greater than 2 mm.

The University of Strathclyde system uses two fixed position cameras, located perpendicular to the walking direction and ahead of the subject, similar to the location of most cine film systems. The television cameras are directly interfaced to the computer so that essentially real time data acquisition and processing is possible. The computational times prohibit displaying information at the exactly the time it is being recorded, but the few seconds of delay are insignificant when compared to cine film processing times. This system also allows an immediate repetition of a particular test if any problems arise during the test session as preliminary results are available for analysis.

Although the initial cost of TV systems is much higher than conventional cine film systems, primarily because of the cost of the supporting computer, the long term cost per test is probably much less. The major advantage is the availability of a system for conducting a large number of repetitive tests on a single subject or testing a large number of subjects. Most kinematic studies to date have involved relatively few subjects and those using a significant number of subjects have taken years to complete.

1.4.5 Body Contact Systems

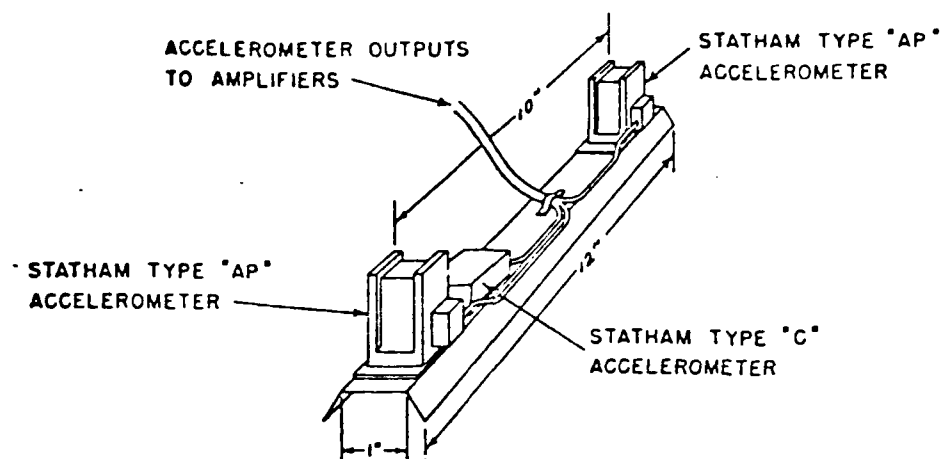
One of the least expensive and simple devices for measuring relative motion between two body segments at a joint is the goniometer as used by Karpovich(1960). A precision potentiometer is mounted on a mechanical supporting bracket and the shaft is fixed to another support bracket. The two brackets are then fixed on either side of a joint and the variation in resistance is directly proportional to the angle between the brackets. When suitable calibrated, no data reduction is necessary as the angle is output directly and can be recorded on a simple chart recorder. More than one goniometer can be incorporated in a single system and one of the more complex systems was the exoskeleton devised by Lamoreux(1971) to measure the rotations of the hip, knee and ankle. This system required precise alignment of the hip linkages to ensure that the effective center of the device coincided with the center of the hip joint. Earlier linkages used at the knee also required careful alignment, but later linkage systems were devised which did not require precise alignment as reported in Radcliffe(1974). These devices are called self-aligning goniometers and provide a simple method for obtaining direct measurement of the relative angles at a joint.

Another simple device based on the potentiometer measures the absolute or relative position of a point on the body. One end of a string is attached to the shaft of the potentiometer and the other end to a desired anatomical point on the subject's body. As the subject moves the output of the potentiometer is proportional to the position of this point referred to some initial position. This method was used by Lamoreux(1971), as discussed in the previous section, to measure the translation and rotation of the pelvis of a subject walking on a treadmill. The major source of error is sag in the string, but the method is simple and inexpensive.

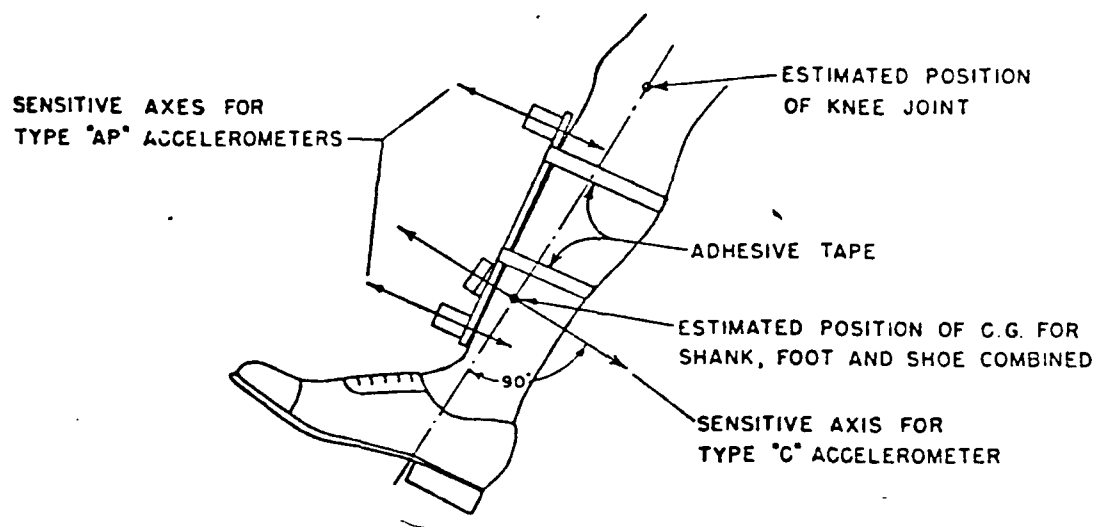
A similar device was used by Drillis(1958) to measure the horizontal velocity of the trunk. In this study a DC generator, or tachograph, was driven by a string attached to the subject instead of a potentiometer. The output voltage is directly proportional to the velocity of the point on the body to which the string is attached. Molen(1972) modified this method to record the instantaneous velocity of the body's center of gravity. He prerecorded pulses at a fixed frequency and constant speed on magnetic tape which he then attached to the front and rear of a subject. The tape was looped over guides and a tape read head and the subject walking moved the tape over the read heads. The output frequency, converted to a DC voltage, was directly proportional to the instantaneous velocity of the tape passing over the read head and therefore the instantaneous velocity of the subject.

These devices are simple and inexpensive; however they provide only limited information on the kinematics of the lower limbs and pelvis during locomotion. Other methods in addition to those discussed in this review have been used or proposed for use in kinematic studies of locomotion and body movement. These include magnetometers proposed by Page(1973), cine radiographic techniques by Eberhart(1951) and other techniques which either require invasive methods or did not seem practical to the author for use in this study.

The other body contact method consistently mentioned in the literature was the use of accelerometers. The review of this literature will be presented in the final section of this chapter.



(a) ACCELEROMETER MOUNTING ASSEMBLY



(b) ACCELEROMETER MOUNTING ASSEMBLY ON SHANK

Figure 1-16. Accelerometer Mounting
(from Ryker & Bartholomew)

1.5 Review of Previous Studies using Accelerometers

A number of studies have been made in which accelerometers were used to measure different aspects of human locomotion and other medical applications in which acceleration can be used as a diagnostic aid. This review will summarize only those studies which relate directly to the measurement of some aspect of human locomotion or movement of other body members in which accelerometers were used as the principal measuring device.

Many different measurement systems were used in the comprehensive study of human locomotion at the University of California at Berkeley. In 1951 Ryker and Bartholomew reported on the use of accelerometers to measure the angular acceleration of the shank, of either a normal or prosthetic leg, and the linear acceleration of the shank in the sagittal plane. These measurements would then be used to evaluate the performance of various knee joint mechanisms in prostheses. During swing phase, the knee joint moment is a function of these parameters and if direct measurement could be accomplished the calculation of knee moment would be simplified. The accelerometer mounting and the method of mounting the device on the shank are shown in Figure 1-16. Very extensive tests of the range and sensitivity of the system as well as frequency response testing of the system were reported in the study. The estimated accuracy of the system, for both angular and linear measurements, was 6%. Typical test data for one subject were included in the report and it was pointed out that there was no method to correct the data for the effect of gravity unless simultaneous cine film data were taken and the position information on the shank obtained from analysis of the cine film. The report concluded from these tests that for the determination of energy transfers occurring

in the lower limbs during walking

"...for the foot, shank and thigh the required number of accelerometers is too great to make the method practical. Motion picture data and grapho-numerical differentiation, however, provide all the necessary kinematic quantities with sufficient accuracy...."

They go on to state that for evaluating knee joint mechanisms

"Motion picture data and grapho-numerical differentiation may be used instead, but the time required to produce results and the loss of accuracy make this method impractical for extensive use in rapid evaluation of knee mechanisms.

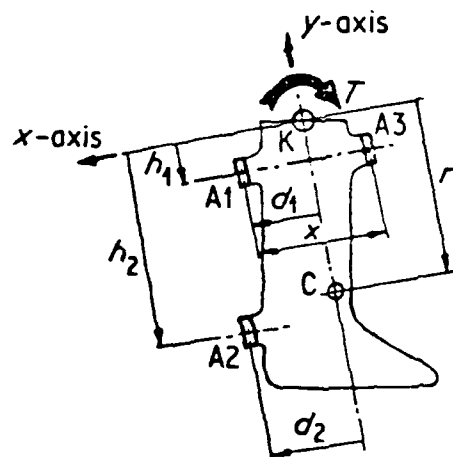
Accelerometers, on the other hand, are well adapted to this purpose and the use of this method is indicated."

This study seems to indicate that except where acceleration is the primary quantity to be measured other gait analysis methods are more suitable for acquiring data.

In 1966 Moffat also reported using accelerometers to determine prosthetic knee moment. The apparatus included a potentiometer to measure the knee angle and this signal was differentiated to provide the knee angular velocity. The accelerometers were used to measure the angular acceleration of the shank. The method also required determining the mass, radius of gyration and centroidal distance for the prosthesis being tested. These were determined by weighing the prosthesis, then oscillating it as a simple pendulum and measuring the period of oscillation and finally suspending it to determine the center of mass. After these quantities were determined, the accelerometer apparatus was attached to the subject who then walked a straight and level distance while data were recorded on chart recorders through a cable. Eight subjects were tested and several suggestions for improving knee joint prostheses are made. The author concludes with

"...causes the amputee to alter the term \ddot{R} , the acceleration of the knee joint. In this way a gait defect initiating at the knee joint is transmitted to the pelvis and the entire body."

This conclusion seems to indicate that variations in pelvic motion could



Note that the sensitive axis of accelerometer A1 is colinear with that of accelerometer A3

$$T = Aa_1 + Ba_2 + C(a_3 - a_1)$$

Where

$$A = m(rh_2 - k^2) / (h_2 - h_1)$$

$$B = m(k^2 - rh_1) / (h_2 - h_1)$$

$$C = (Ad_1 + Bd_2) / x$$

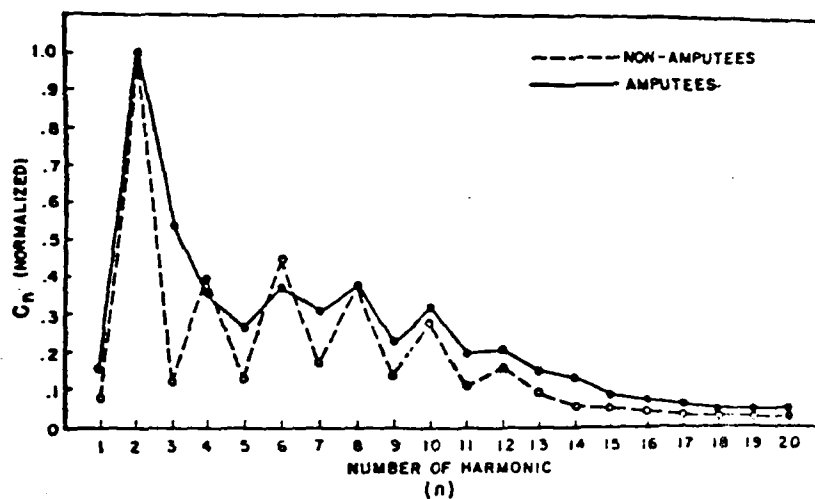
and a_1, a_2, a_3 are the linear accelerations recorded by accelerometers A1, A2, A3 respectively

Figure 1-17. The BRADU Method
(from Judge)

indicate lower joint defects.

A further refinement of these techniques was implemented in 1976 by Judge at the Biomechanical Research and Development Unit in Roehampton. The purpose of this study was to investigate and quantify the effects of making adjustments to current knee control units installed in above knee artificial legs and to predict desirable characteristics for future designs. The apparatus was designed to be used on both above and below knee prostheses. In this study three accelerometers were used to provide the necessary data for computing the swing phase knee torque mounted as shown in Figure 1-17. The accelerometer outputs were input directly to a set of suitable scaled analog computers and the results were therefore available in real time. No results of patient testing were reported, however this method corrects some of the errors found in the earlier studies and should produce useful information.

In 1962 Liberson, et.al. reported a study in which accelerometers were attached not only to the shank, but also to the chest and thigh. The accelerometers were attached to the shank to obtain angular acceleration information and linear accelerations. This study resulted from Liberson's original development in 1936 of a technique for directly recording accelerations of the body. This is the earliest reference in the literature of accelerometers being used to study body movement. The study of 1962 reports on early results from testing 10 hemiplegic patients and 10 above knee amputees. The resulting acceleration patterns were compared with normal subjects and the authors indicate that the method would be suitable for training to improve the gait of the patients. No further results have been published to indicate if this system is still being utilized for this purpose.



Harmonic analysis of vertical accelerations, level walking. Curves represent mean values

Figure 1-18. Harmonic Analysis
(from Gage)

A similar study to use acceleration as an indicator of normal and abnormal gait was reported by Gage in 1964. In this study accelerometers were attached to the trunk at the S-2 level to measure accelerations in the vertical and anterior-posterior directions. Additional accelerometers were attached to the shank to measure the angular acceleration of the shank in the sagittal plane. The acceleration patterns for both normal subjects and amputees are presented and the concept of using harmonic analysis to analyze gait defects is presented. The results of harmonic analysis of the vertical acceleration for amputees and normal subjects is shown in Figure 1-18. The author reports on some preliminary correlation of specific gait defects with specific odd harmonics however, he states that they are based on a limited number of subjects and that further investigations should be made.

This method of recording body accelerations and analyzing the resulting patterns using harmonic analysis has been actively pursued at the University of Iowa by Smidt. The first results were reported in 1971 for fifteen normal adults, seven normal boys and five patients with gait defects. The apparatus consisted of three accelerometers which were mounted to the sacrum using double sided adhesive tape and a leather belt to provide additional stabilization. A footswitch was used in conjunction with the accelerometers to record heel strike information. This study introduced the harmonic ratio, obtained by dividing the coefficients of the even harmonics by the coefficients of the odd harmonics, as an indicator of the smoothness of the gait pattern. The following scale was an attempt to classify the smoothness of walking: greater than 2.00 is normal, 1.50 to 2.00 is fair, 1.00 to 1.49 is poor, and less than 1.0 is very poor. Small groups of subjects using crutches and with induced impairments were also studied and the results of these tests formed the basis for the harmonic ratio scale.

A second study of nineteen below-knee amputees was completed by Robinson(1972). The mean harmonic ratio was 1.63 for the anterior-posterior and 1.55 for the vertical accelerations. These values agree with the scale established in the first study and the author states that these low values

"....have an implication demonstrating the need for improved gait training, proper fitting of prostheses, and improved mass distribution properties in prostheses."

The comment is also made that the method of performing harmonic analysis on the acceleration patterns is cumbersome and time consuming indicating the lack of modern computer facilities at that time. This study was reported in the literature, Robinson, et.al.(1977).

The efforts to correct and automate the data analysis of acceleration patterns were published in 1977 by Smidt, et.al. The outputs of the accelerometers and footswitches were input directly to a PDP-12 computer through an amplifier-power supply interface. The computer was set to begin sampling data automatically at the second right heelstrike and collected data for one complete cycle. Three walking cycles were collected and stored on magnetic tape for processing. The initial processing to compute temporal and distance factors relating to walking and the peak acceleration values required about 15 minutes per patient. The author does not indicate how much time was required to obtain the harmonic analysis which completed data processing, but this was also accomplished with the computer. This study included a test of the accuracy of the accelerometers in which the displacement of the accelerometer package was photographed while simultaneously recording the output of the accelerometers. The triaxial accelerometer was moved by hand in a straight line on a horizontal vinyl surface for distances from 35.6 to 45.7 cm. The displacement data were then double differentiated to obtain velocity and acceleration curves and the results compared with the accelerometer output

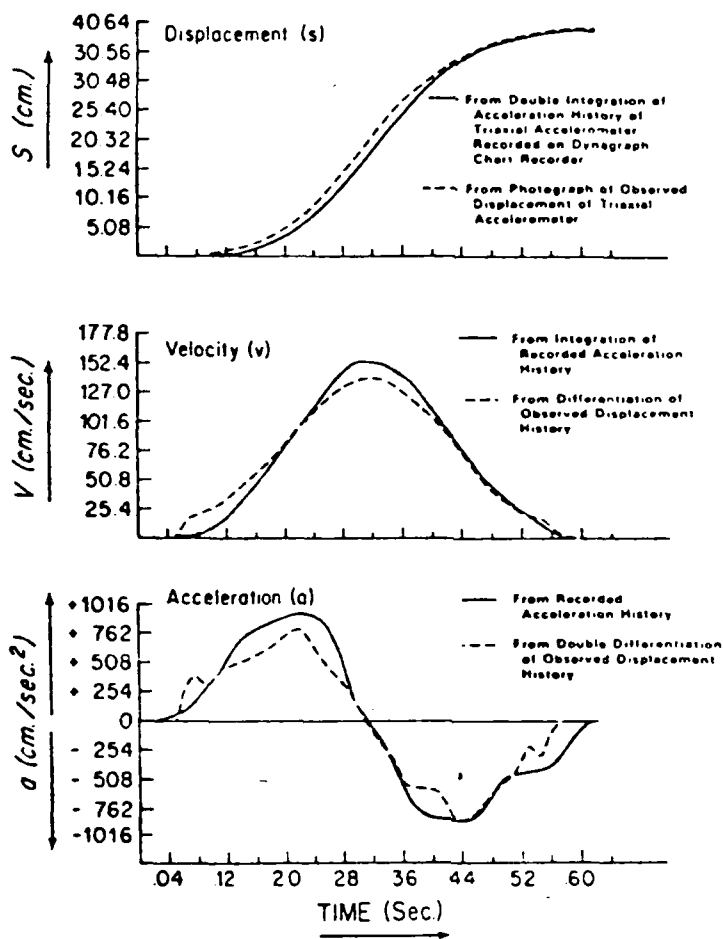


Figure 1-19. Accelerometer and Displacement Tests
(from Smidt, et.al.)

as shown in Figure 1-19. The error for displacement is the smallest and the authors report that the increasing discrepancy from displacement to velocity to acceleration is due to the magnification of minute errors in the photographic procedure which are then magnified at each stage of the differentiation procedure. This is in agreement with the statements of other authors that integration decreases errors while differentiation magnifies them. Preliminary results of using the system to evaluate the gait patterns of tibio-femoral knee implants was reported. The subjects were tested preoperatively and at two, six and 12 months following surgery. Twenty two patients with degenerative joint disease and 24 patients with rheumatoid arthritis were studied and the harmonic ratio of the degenerative group improved to a value of nearly 2.5 which Smidt classifies as fair to good. The rheumatoid arthritics value was not reported, but it was "less impressive."

Another investigation using accelerometers was begun at the University of Milan, Italy by Cavagna, Saibene and Margaria in 1961. They reported the development of a three-directional accelerometer to be used in analyzing body movements by recording accelerations. The first results were reported in 1963 in which the accelerometer was mounted on the sacrum, using a belt, to measure accelerations and motion pictures, taken simultaneously, were used to record the displacement of the center of gravity of the body. These data were then used to compute the external work performed in walking. A graphic integration technique was used to obtain the velocity and displacement of the body. The results of this study indicate that walking is most efficient, in terms of work done, at 4 km/hr and slowing down or speeding up from this speed requires an increased energy expenditure. This group reported a second study

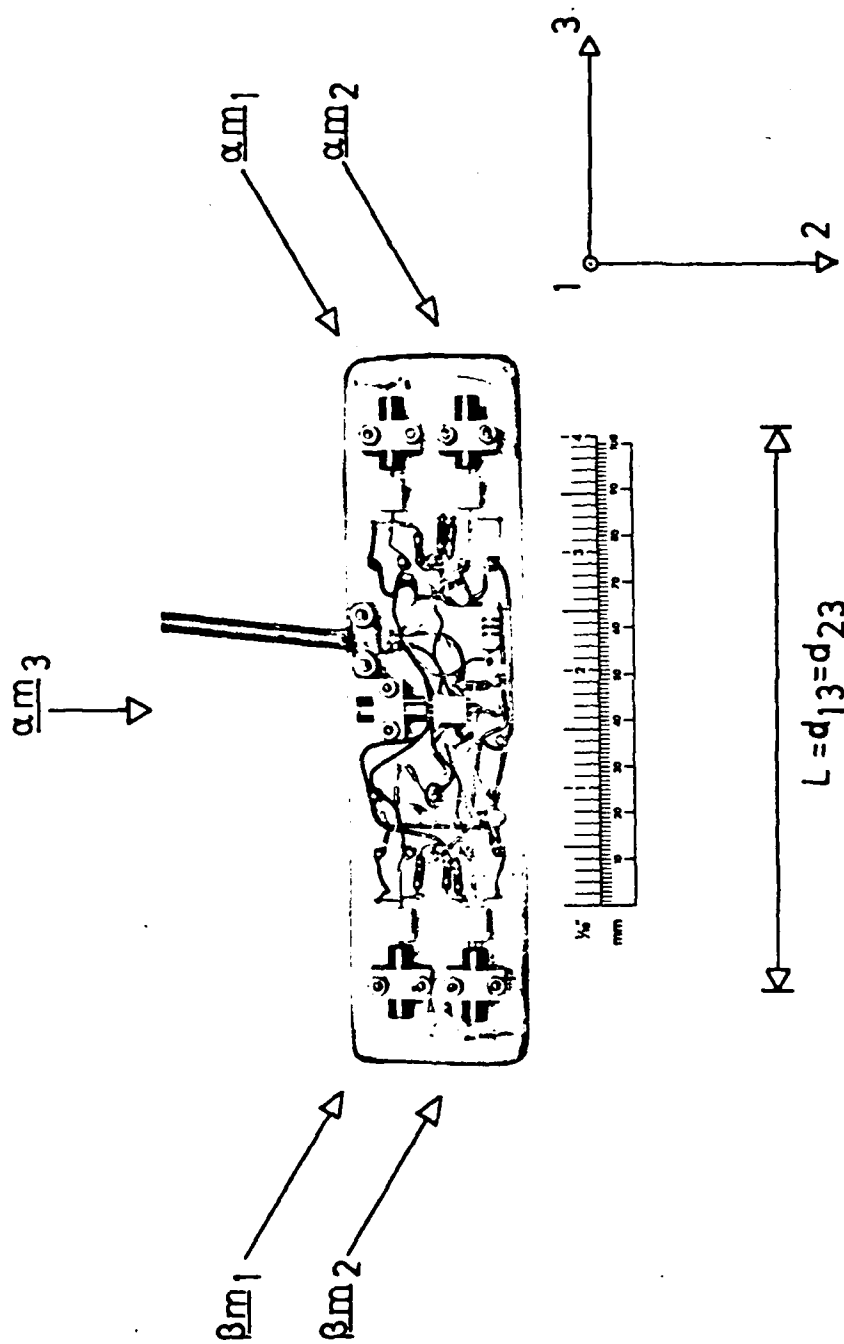


Figure 1-20. Five Accelerometer Platform
(from Morris)

of work in 1966 using force plates rather than accelerometers in which they state

"This method(viz force plates) seems more convenient and more direct than the accelerometric or the moving-pictures method employed in the earlier work."

In a separate study of the external work in walking, Gersten(1969), reported using only accelerometers and heel switches to make the measurements required to compute work. Three accelerometers were attached to the sacrum and the acceleration data were punched on computer cards by a digital interface unit and card punch machine. The cards were then used to input the data to the computer for processing. The accelerometers were aligned by installing shims to ensure that the vertical accelerometer was aligned with the local gravity vector and the acceleration due to gravity was then added to the output of the vertical accelerometer. The average forward velocity was obtained by integrating the anterior-posterior accelerometer output. The errors in accelerometer position due to body movement during walking were corrected by assuming oscillations of 3° in the sagittal plane, 8° in the transverse plane and 10° in the coronal plane. The author reports that the average work values were slightly higher than those reported by Cavagna, et.al. This system was also reported to be capable of reducing the accelerometer data to external work and print the results "while the subjects were walking."

The first study to obtain position information from accelerometer measurements was begun at Oxford in 1970 by Morris and results were published in 1973. The purpose of this study was to investigate the feasibility of accelerometry as a technique for determining angular and translational positions of a body segment, in this case the shank. Five accelerometers were attached to the shank and linear acceleration, velocity and position and angular velocity and position of the shank were

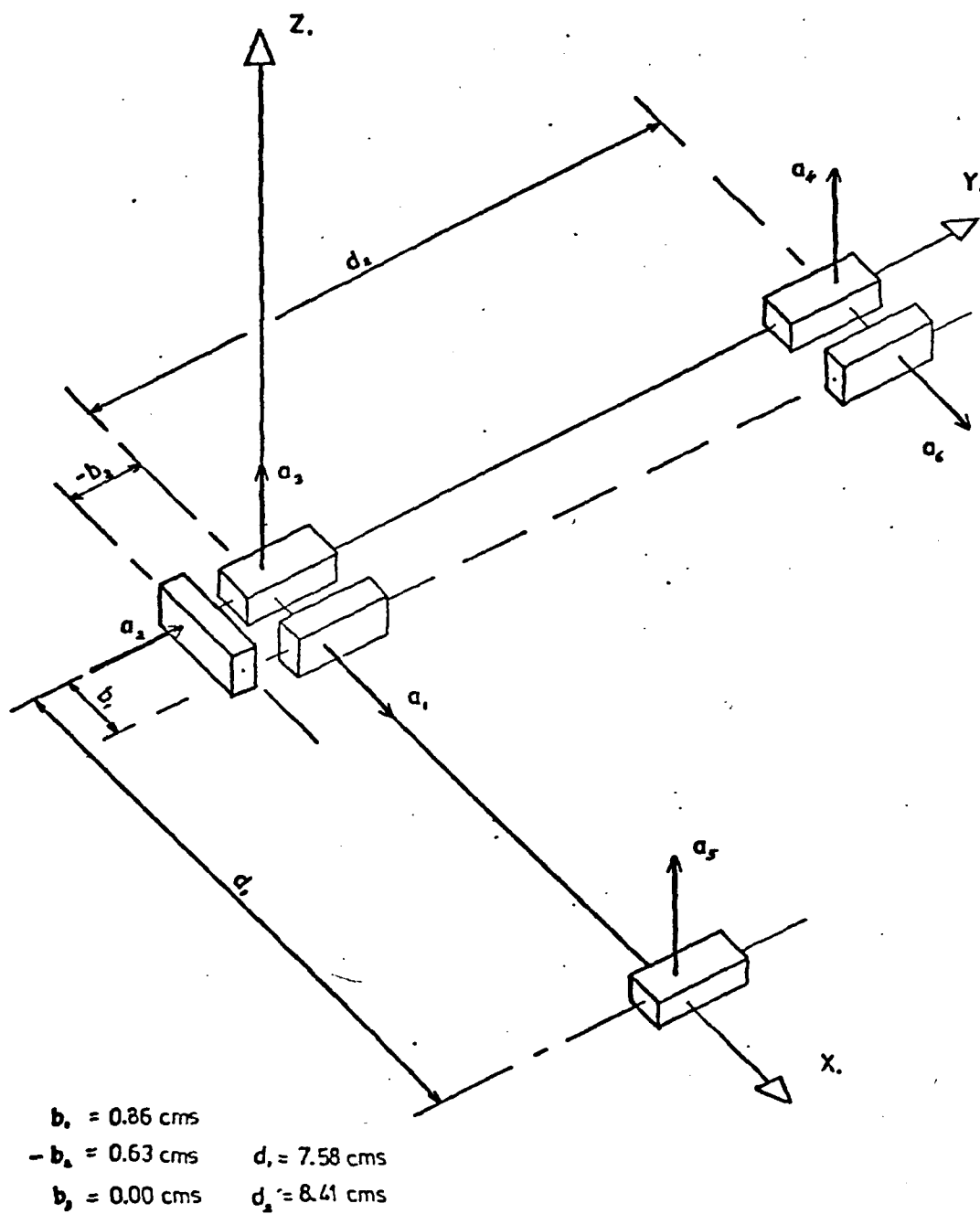


Figure 1-21. Six Accelerometer Configuration
(from Mitchell)

determined in two dimensions(sagittal plane motion). The accelerometer apparatus is shown in Figure 1-20. The mathematical analysis used is similar to that discussed in chapter 2 of this study, although simplifying assumptions were made to reduce it to two dimensions. The signals were recorded on magnetic tape and analyzed using interactive computer programs in which the operator selected single step cycles for analysis. This study reported that the angular and translational velocities of the shank "reveal the most about the gait of the subject." These quantities are difficult to obtain accurately from standard cine film or interrupted light studies. This study also showed that accelerometer data could be used to provide not only acceleration information, but also velocity and position information for a body segment.

Similar research at the University of Strathclyde was reported by Mitchell in 1975. In this study, a six accelerometer configuration for measuring the position of the shank in three dimensions was tested. The basic theory used was very similar to that described in chapter 2 of this study, but a different configuration of the accelerometers was used as shown in Figure 1-21. The accelerometer apparatus and associated electronic circuitry were constructed and the performance of the system was evaluated on a mechanical four-bar linkage device which simulated the motion of the human shank. No computer programs were developed other than those used in the test to compute angular acceleration and the correlation between the calculated and measured accelerations was acceptable. There seems to have been no further development of this system.

A completely independent investigation into techniques of measuring rigid body motion with accelerometers was reported in 1975 by Padgaonkar, et.al. The purpose of this research was to develop an all accelerometer measuring system to measure the motion of the head of either an anthropomorphic dummy or human volunteer under impact conditions. The

impacts were normally those associated with automobile accidents and testing was carried out using a sled rail facility. They reported that in high impact environments the six accelerometer system will not produce accurate results and becomes unstable. They therefore developed a nine accelerometer configuration to eliminate the nonlinear terms in the equations and allow direct integration of the measured accelerations. In a letter Liu(1976) concludes that the system of nonlinear equations for the six accelerometer configuration are unstable and further states

"...one can further assert that no amount of additional manipulation or clever placement of the six accelerometers would yield a set of equations which will be stable."

In a second report of this research by Chou and Sinha in 1976 results of testing the nine accelerometer configuration are presented. This study also states that the equations for the six accelerometer configuration are unstable and that difficulties with numerical integration methods precluded obtaining reliable or useful results. The study does report on the calculation of angular velocity of the head and compares results obtained from the nine accelerometer configuration and three high speed motion picture cameras. They report good qualitative agreement, but the film values are lower than the accelerometer values. The authors also indicate that the method has been applied to studies of flexion, extension and lateral flexion of the neck and results would be reported in the future.

Other body segments have also been studied using accelerometers. In 1966 Ayoub reported measuring the acceleration and velocity of the hand. The study investigated the motion of the hand while industrial tasks of moving different masses from one location on a workbench to another location were performed. Accelerometer measurements were integrated to obtain velocity information, but distance was prescribed in the task to be

performed. The primary purpose was to determine when and where the maximum and minimum acceleration and velocity occurred in performing these tasks.

Other studies reported on impact accelerations which occur in walking when the heel strikes the ground. In 1977 Light and McLellan reported the differences in accelerations due to footwear. They report that both the duration and peak acceleration in the tibia are affected by heel construction and that normal accelerations of 2-8 g's occur in the tibia when walking. Another study by Guenther in 1968 reported the use of accelerometers to investigate impact vibrations in walking and running on various floor surfaces. Accelerometers were attached to the heel, pelvis and head and accelerations varied from 23-31 g's at the heel to 1.1-2.1 g's at the pelvis to 0.6-1.1 g's at the head. The author reports that accelerations at the heel are approximately equal for walking and running, while the running values approach double those for walking at the pelvis and more than double at the head.

This review does not include all the studies which have used accelerometers to measure information of medical or biomedical interest. It has focused on those studies in which accelerometers were used to measure some kinematic parameters of human body movement. The principal interest was in studies of the lower limbs and body using accelerometry.

The theory for implementing the use of accelerometers to obtain kinematic measurements in this study will be presented in the following chapter.

CHAPTER 2

THEORETICAL ANALYSIS

- 2.1 Introduction
- 2.2 General Equations of Rigid Body Motion
- 2.3 The Planar Eight Accelerometer Configuration
- 2.4 Derivation of the Rotational Parameters
- 2.5 Derivation of the Translational Parameters

2.1 Introduction

This chapter presents the theoretical basis for the accelerometer measurement system developed and used in this study. The general equations of rigid body motion are reviewed and the planar eight accelerometer configuration is developed from these general equations. The rotational and translational parameters which describe the motion of a rigid body, in this study the pelvis, are derived and the differential equations used to compute experimental results are developed.

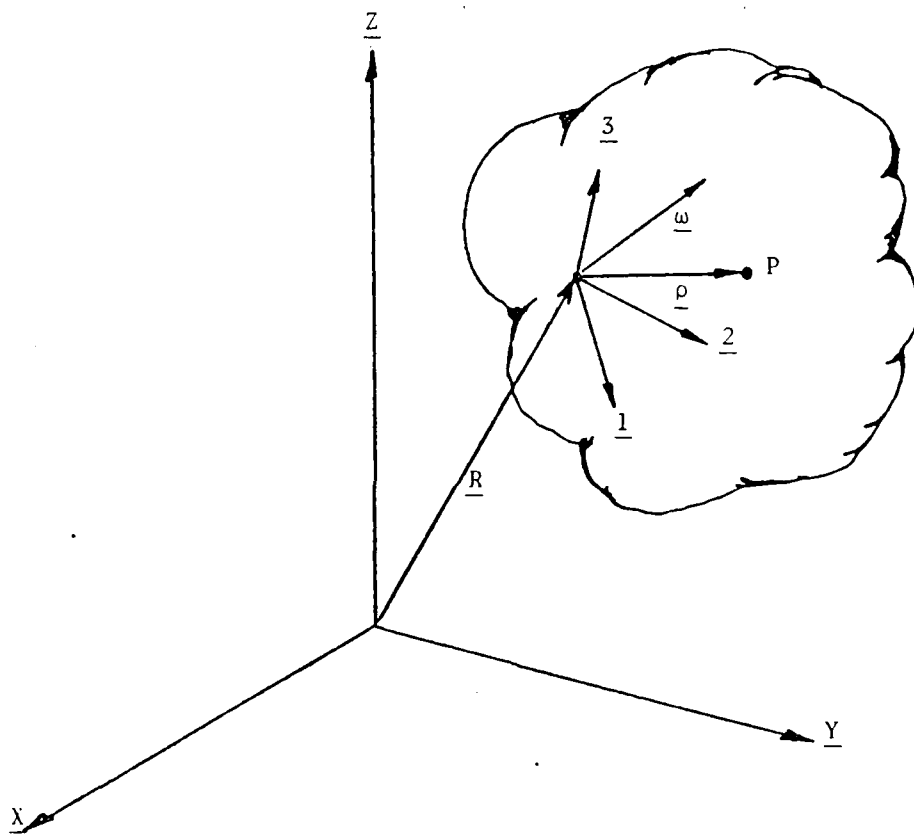


Figure 2-1. General Rigid Body Motion.

2.2 General Equations of Rigid Body Motion

This section is not intended to present a complete and formal derivation of the equations governing rigid body motion, but will briefly summarize the kinematic equations of rigid body motion used in this study. A complete derivation may be found in any good dynamics textbook such as Greenwood(1965) or Goodman and Warner(1963).

In general, a rigid body has six degrees of freedom which can be subdivided into three translational and three rotational modes. The translation of a rigid body can be expressed by three independent coordinates which specify the location of a fixed point in the rigid body. The remaining three degrees of freedom correspond to changes in the orientation of the rigid body and can be described by rotational parameters. This rotational motion is most commonly expressed in terms of direction cosines. A set of direction cosines can completely describe the rotational transformation from the rotated position of the rigid body to the fixed position.

Consider a rigid body moving in space whose location is specified by two cartesian coordinate systems as shown in Figure 2-1. The 1,2,3 coordinate system is located in the rigid body(body-centered system) and moves with it while the X,Y,Z coordinate system is fixed in inertial space(fixed system). The general acceleration experienced by the point P, located in the rigid body, is given by:

$$\ddot{\underline{r}} = \ddot{\underline{R}} + \ddot{\underline{\rho}} + \dot{\underline{\omega}} \times \underline{\rho} + \underline{\omega} \times (\underline{\omega} \times \underline{\rho}) + 2\underline{\omega} \times \dot{\underline{\rho}} \quad (2.1)$$

For a rigid body $\underline{\rho}$ is a constant(ie. $\dot{\underline{\rho}} = \ddot{\underline{\rho}} = 0$) so that

$$\ddot{\underline{r}} = \ddot{\underline{R}} + \dot{\underline{\omega}} \times \underline{\rho} + \underline{\omega} \times (\underline{\omega} \times \underline{\rho}) \quad (2.2)$$

where

$$\ddot{\underline{r}} = \text{acceleration of point P}$$

$$\ddot{\underline{R}} = \text{acceleration of the origin of the body-centered system}$$

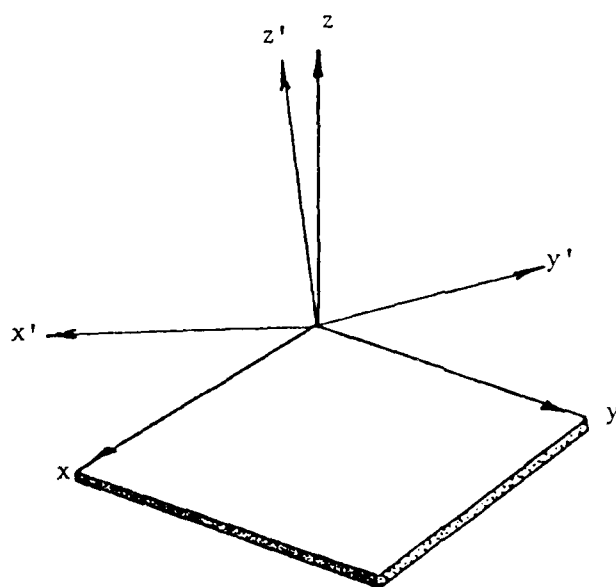


Figure 2-2. Two Coordinate Systems with an Arbitrary Orientation.

$\underline{\omega}$ = angular velocity of the body-centered system relative to the fixed system

$\dot{\underline{\omega}}$ = time rate of change of the angular velocity

$\underline{\rho}$ = position of point P as measured in the body-centered system.

The measured acceleration contains a component due to gravity, thus

$$\underline{a} = \ddot{\underline{r}} + \underline{g} \quad (2.3)$$

where

\underline{a} = acceleration measured by an accelerometer

\underline{g} = acceleration due to gravity.

Thus,

$$\underline{a} = \ddot{\underline{R}} + \dot{\underline{\omega}} \times \underline{\rho} + \underline{\omega} \times (\underline{\omega} \times \underline{\rho}) + \underline{g} \quad (2.4)$$

Transforming vectors from the body-centered system to the fixed system, or vice-versa, requires the use of a rotational transformation matrix and translation of the origin of the coordinate system. In general, the rotational transformation matrix is written as:

$$[T] = \begin{bmatrix} l_{x'x} & l_{x'y} & l_{x'z} \\ l_{y'x} & l_{y'y} & l_{y'z} \\ l_{z'x} & l_{z'y} & l_{z'z} \end{bmatrix} \quad (2.5)$$

where the $l_{i'j}$ represent the cosines of the angles between the primed and unprimed axis systems as shown in Figure 2-2. Now to transform a vector \underline{A}

from the unprimed to the primed system, one only has to perform the following matrix multiplication.

$$\begin{Bmatrix} A_{x'} \\ A_{y'} \\ A_{z'} \end{Bmatrix} \approx [T] \begin{Bmatrix} A_x \\ A_y \\ A_z \end{Bmatrix} \quad (2.6)$$

Since the transformation matrix is an orthogonal matrix, the inverse matrix is equal to the transpose matrix and the transformation from the primed to the unprimed system can be made by using

$$\begin{Bmatrix} A_x \\ A_y \\ A_z \end{Bmatrix} = [T^{-1}] \begin{Bmatrix} A_{x'} \\ A_{y'} \\ A_{z'} \end{Bmatrix} \quad (2.7)$$

The transformation matrix used in this study will be derived in section 2.4.

The calculation of position and velocity from acceleration is accomplished by integrating the acceleration to obtain velocity

$$\underline{v} = \int (\underline{a} - \underline{g}) dt + \underline{v}_0 \quad (2.8)$$

and then integrating the velocity to obtain position

$$\underline{r} = \int \underline{v} dt + \underline{r}_0 \quad (2.9)$$

The acceleration must be determined in a fixed or inertial coordinate system and the initial velocity, \underline{v}_0 , and position, \underline{r}_0 , must be known in order to perform the above integrations.

The specific equations of motion used in this study will now be derived from these general equations of rigid body motion.

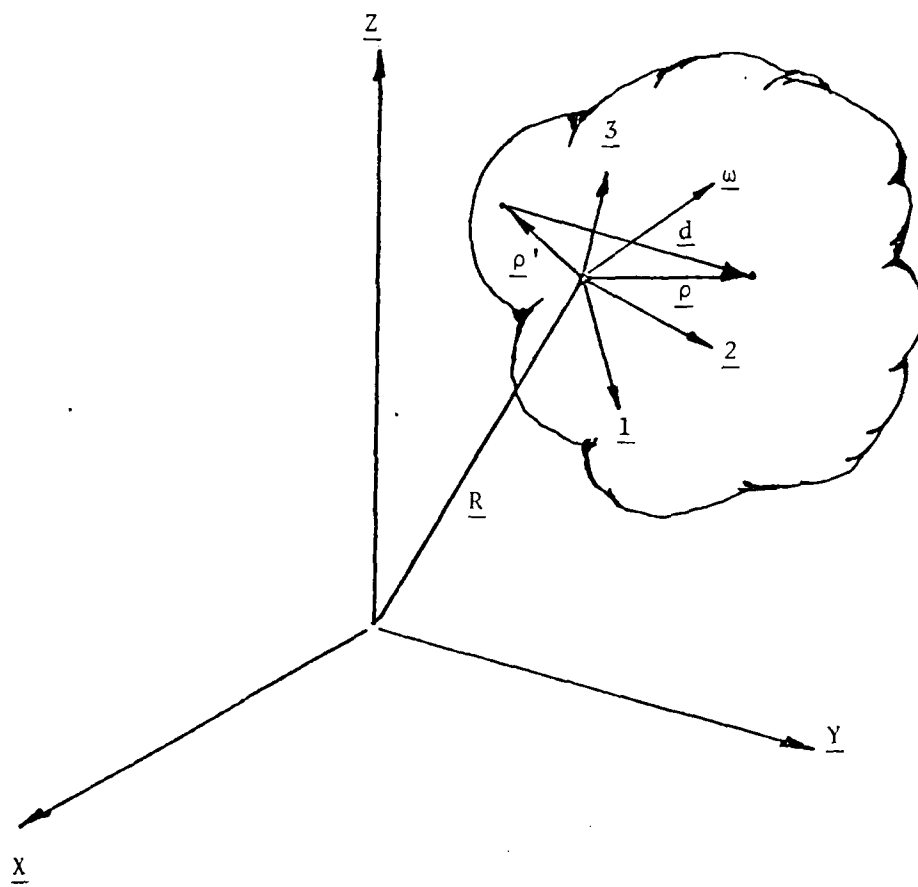


Figure 2-3. The Vector Representation of Two Points Located on a Rigid Body.

2.3 The Planar Eight Accelerometer Configuration

In most inertial measurement systems the rotational parameters are measured with gyroscopes and the translational parameters with accelerometers. However, it is possible to eliminate the gyroscopes and measure the rotational parameters with pairs of accelerometers located on the rigid body.

If pairs of accelerometers are used to measure \underline{a} at position \underline{p} and \underline{a}' at position \underline{p}' , then from equation (2.4)

$$\underline{a} = \ddot{\underline{R}} + \dot{\underline{\omega}} \times \underline{p} + \underline{\omega} \times (\underline{\omega} \times \underline{p}) + \underline{g} \quad (2.10)$$

and

$$\underline{a}' = \ddot{\underline{R}} + \dot{\underline{\omega}} \times \underline{p}' + \underline{\omega} \times (\underline{\omega} \times \underline{p}') + \underline{g} \quad (2.11)$$

Now if the outputs of these accelerometers are subtracted

$$\underline{a} - \underline{a}' = \dot{\underline{\omega}} \times (\underline{p} - \underline{p}') + \underline{\omega} \times [\underline{\omega} \times (\underline{p} - \underline{p}')] \quad (2.12)$$

then the translational terms are eliminated and only the rotational components remain. Let

$$\underline{\alpha} = \underline{a} - \underline{a}' \quad \text{and} \quad \underline{d} = \underline{p} - \underline{p}'$$

so that

$$\underline{\alpha} = \dot{\underline{\omega}} \times \underline{d} + \underline{\omega} \times (\underline{\omega} \times \underline{d}) \quad (2.13)$$

This equation relates the acceleration difference $\underline{\alpha}$ measured at two points separated by distance \underline{d} on a rigid body rotating at angular velocity $\underline{\omega}$ as shown in Figure 2-3.

Now expand equation (2.13) into three scalar equations by performing the indicated vector operations. The cross product is

$$\dot{\underline{\omega}} \times \underline{d} = (\dot{\omega}_2 d_3 - \dot{\omega}_3 d_2) \underline{1} + (\dot{\omega}_3 d_1 - \dot{\omega}_1 d_3) \underline{2} + (\dot{\omega}_1 d_2 - \dot{\omega}_2 d_1) \underline{3} \quad (2.14)$$

Similarly one obtains for the double cross product term

$$\begin{aligned} \underline{\omega} \times (\underline{\omega} \times \underline{d}) = & [\omega_1 \omega_2 d_2 + \omega_1 \omega_3 d_3 - (\omega_2^2 + \omega_3^2) d_1] \underline{1} \\ & + [\omega_1 \omega_2 d_1 + \omega_2 \omega_3 d_3 - (\omega_1^2 + \omega_3^2) d_2] \underline{2} \\ & + [\omega_1 \omega_3 d_1 + \omega_2 \omega_3 d_2 - (\omega_1^2 + \omega_2^2) d_3] \underline{3} \end{aligned} \quad (2.15)$$

To form the scalar equations, it is convenient to add a second subscript

to the d_i terms to indicate not only the axis direction, but also the axis on which the accelerometer pairs are located. The scalar equations equivalent to equation (2.13) are

$$\alpha_1 = \dot{\omega}_2 d_{13} + \omega_1 \omega_3 d_{13} - \dot{\omega}_3 d_{12} + \omega_1 \omega_2 d_{12} - (\omega_2^2 + \omega_3^2) d_{11} \quad (2.16)$$

$$\alpha_2 = \dot{\omega}_3 d_{21} + \omega_1 \omega_2 d_{21} - \dot{\omega}_1 d_{23} + \omega_2 \omega_3 d_{23} - (\omega_1^2 + \omega_3^2) d_{22} \quad (2.17)$$

$$\alpha_3 = \dot{\omega}_1 d_{32} + \omega_2 \omega_3 d_{32} - \dot{\omega}_2 d_{31} + \omega_1 \omega_3 d_{31} - (\omega_1^2 + \omega_2^2) d_{33} \quad (2.18)$$

where

single or first subscript = accelerometer measurement direction
in body-centered system
second subscript = axis on which the accelerometer
pair is located

There are nine accelerometer pair locations specified by the d_{ij} terms in these equations. Since the system has six degrees of freedom, only three pair locations must be retained to solve the equations.

For this study it was desirable that the measurement system be as compact in size as possible. Therefore, all accelerometer pairs were located in one plane, the 1-3 plane, so that all $d_{12} = 0$, thus:

$$\alpha_1 = \dot{\omega}_2 d_{13} + \omega_1 \omega_3 d_{13} - (\omega_2^2 + \omega_3^2) d_{11} \quad (2.19)$$

$$\alpha_2 = \dot{\omega}_3 d_{21} + \omega_1 \omega_2 d_{21} - \dot{\omega}_1 d_{23} + \omega_2 \omega_3 d_{23} \quad (2.20)$$

$$\alpha_3 = -\dot{\omega}_2 d_{31} + \omega_1 \omega_3 d_{31} - (\omega_1^2 + \omega_2^2) d_{33} \quad (2.21)$$

Theoretically the solutions to equations (2.19), (2.20) and (2.21) require only six independent measurements (ie. three accelerometer pairs) and there are six pair locations remaining. Other studies by Grammaticos(1965) and Schuler(1965) have shown that if the ω^2 terms are retained additional sensors must be included to determine the direction of the components of the angular velocity $\underline{\omega}$. This is a result of the mathematical operation of taking a square root

$$\omega_k = + \sqrt{-\omega_j^2 - \alpha_i / d_{ii}} \quad \text{or} \quad - \sqrt{-\omega_j^2 - \alpha_i / d_{ii}} \quad (2.22)$$

which requires the additional sensor to determine if the resultant ω_k is

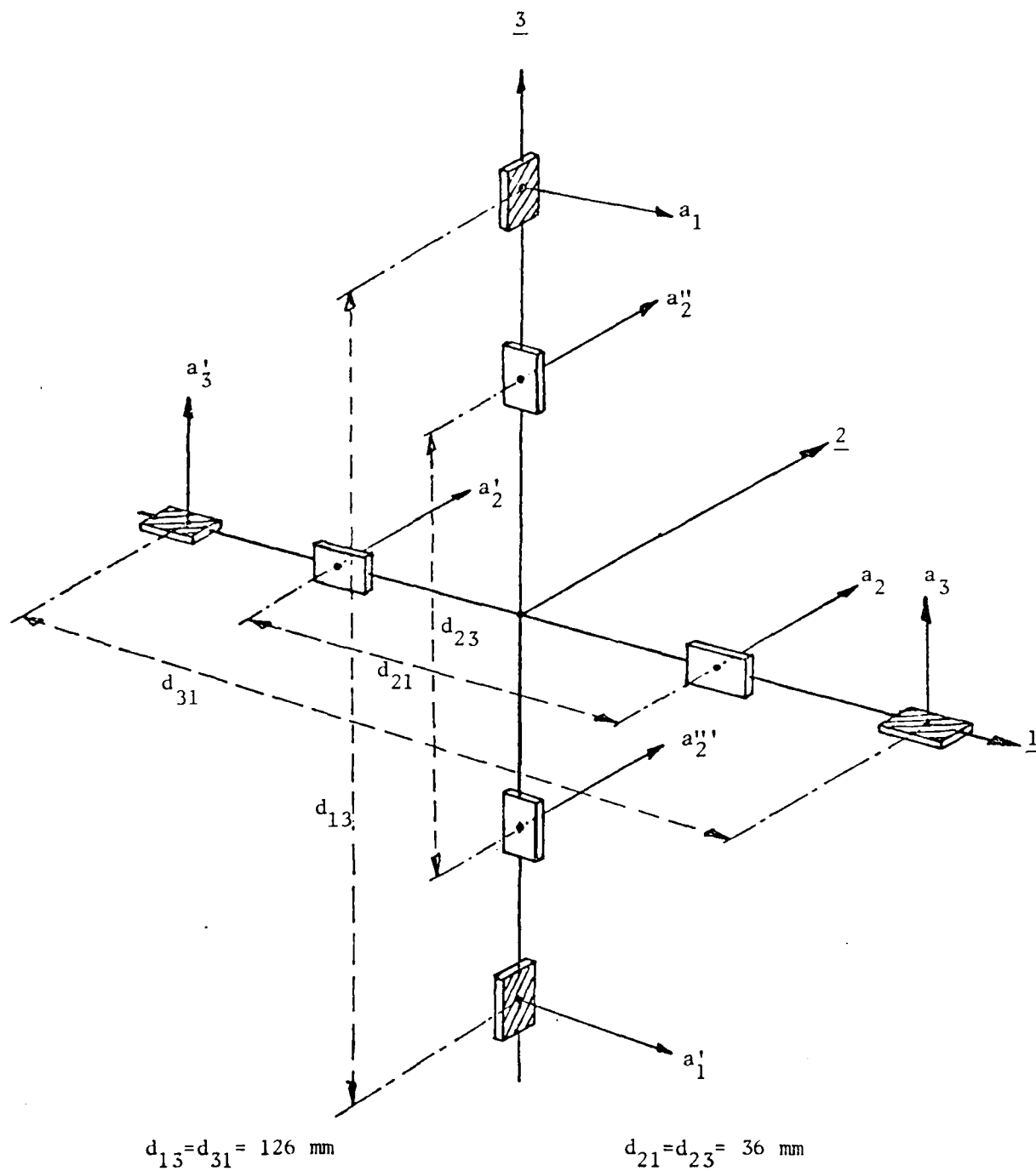


Figure 2-4. The Planar Eight Accelerometer Configuration

positive or negative. Eliminating the accelerometer pair locations involving squared terms, ie. $d_{11} = d_{33} = 0$, results in

$$\alpha_1 = \dot{\omega}_2 d_{13} + \omega_1 \omega_3 d_{13} \quad (2.23)$$

$$\alpha_2 = \dot{\omega}_3 d_{21} + \omega_1 \omega_2 d_{21} - \dot{\omega}_1 d_{23} + \omega_2 \omega_3 d_{23} \quad (2.24)$$

$$\alpha_3 = - \dot{\omega}_2 d_{31} + \omega_1 \omega_3 d_{31} \quad (2.25)$$

There now remains one redundant accelerometer pair location. Before eliminating this pair, it is useful to observe that if $d_{13} = d_{31}$ then subtracting equation (2.25) from (2.23) results in

$$\dot{\omega}_2 = (\alpha_1 - \alpha_3)/2d_{13} \quad (2.26)$$

Therefore, if both locations d_{13} and d_{31} are retained for accelerometer pairs, ω_2 has been uncoupled from ω_1 and ω_3 and can be computed by direct integration of equation (2.26). Equation (2.24) contains two accelerometer pair locations; one pair d_{21} located on the 1 axis and the other pair d_{23} located on the 3 axis. The corresponding equations are:

$$\alpha_2 = \dot{\omega}_3 d_{21} + \omega_1 \omega_2 d_{21} \quad (2.27)$$

$$\alpha_2' = - \dot{\omega}_1 d_{23} + \omega_2 \omega_3 d_{23} \quad (2.28)$$

or rearranging yields

$$\dot{\omega}_1 = \omega_2 \omega_3 - \alpha_2'/d_{23} \quad (2.29)$$

$$\dot{\omega}_3 = - \omega_1 \omega_2 + \alpha_2/d_{21} \quad (2.30)$$

Thus, using eight accelerometers (four pairs) mounted in a single plane, the three first order, non-linear differential equations which may be solved for the components of $\underline{\omega}$ are:

$$\dot{\omega}_1 = \omega_2 \omega_3 - \alpha_2'/d_{23} \quad (2.31)$$

$$\dot{\omega}_2 = (\alpha_1 - \alpha_3)/2d_{13} \quad (2.32)$$

$$\dot{\omega}_3 = - \omega_1 \omega_2 + \alpha_2/d_{21} \quad (2.33)$$

The corresponding accelerometer layout is shown in Figure 2-4.

The solution of equations (2.31), (2.32) and (2.33) for the angular velocity $\underline{\omega}$ is accomplished by:

- (1) measuring the distances d_{13} , d_{21} and d_{23}
- (2) determining the initial values of α_1 , α_2 and α_3
- (3) measuring and recording the accelerometer outputs
- (4) integrating the set of differential equations.

The result is the angular velocity vector

$$\underline{\omega} = \omega_1 \underline{1} + \omega_2 \underline{2} + \omega_3 \underline{3} \quad (2.34)$$

for the body-centered system relative to the fixed system. With the angular velocity of the systems determined, one can now solve for the rotational parameters; the transformation matrix and the orientation angles.

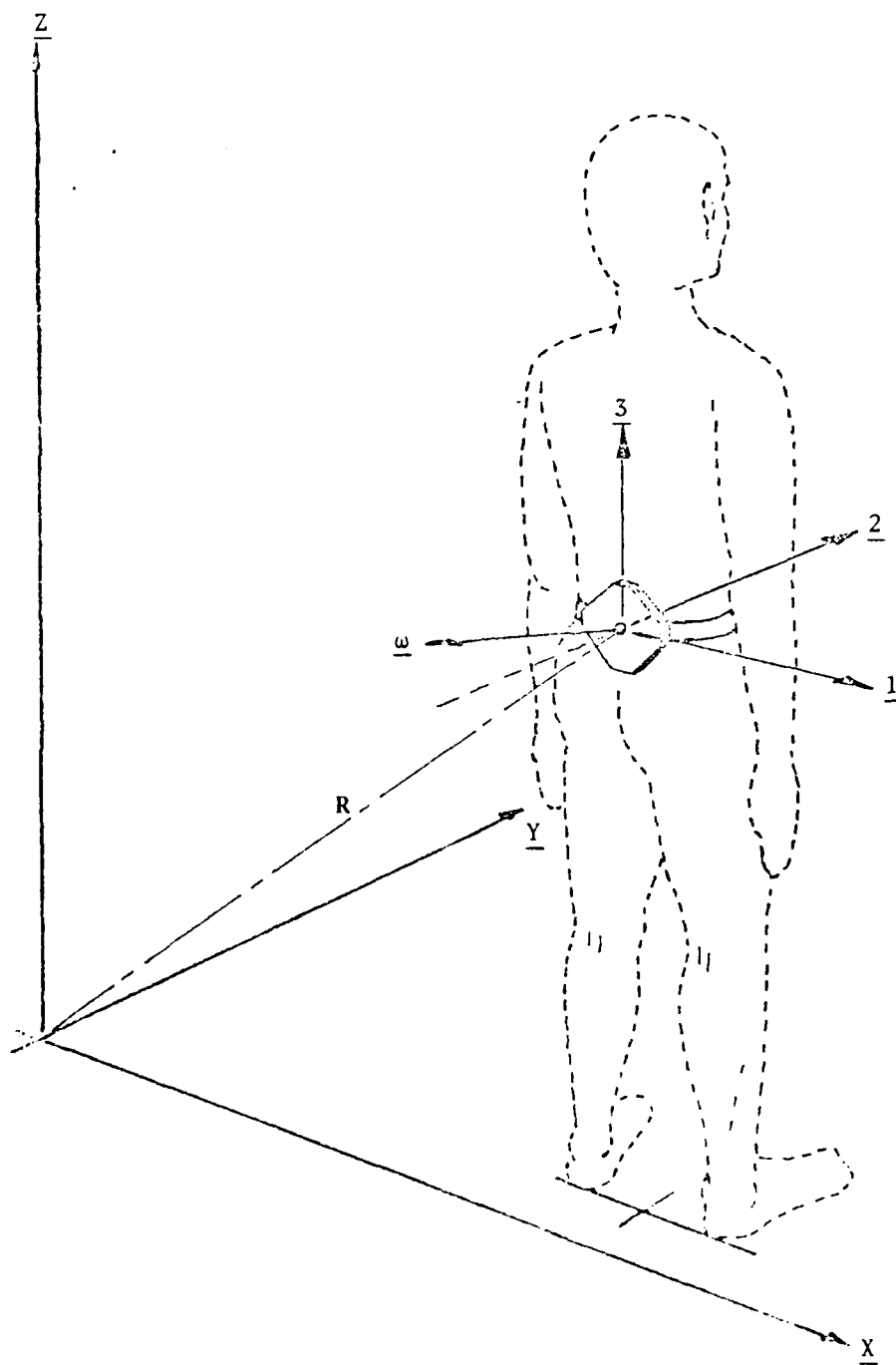


Figure 2-5. The Body-centered and Fixed Coordinate Systems.

2.4 Derivation of the Rotational Parameters

The orientation of the body-centered (1,2,3) system relative to the fixed (X,Y,Z) system, as shown in Figure 2-5, can be expressed by several different sets of parameters. Three such sets, as discussed in NASA CR-968(1968), are

- (1) nine direction cosines which relate each of the body-centered axes to the fixed axes
- (2) four quaternians which include a unit vector specifying the axis of rotation and a scalar specifying the magnitude of the angle of rotation
- (3) three Euler angles which indicate successive rotations about the body-centered axes in a specified sequence.

The general computational scheme of each of these sets is discussed and the set of parameters used in this study are developed.

Let C_R^B represent the transformation matrix required to convert a vector V_B expressed in body-centered coordinates to the parallel vector V_R expressed in fixed coordinates where the transformation is given by

$$V_R = C_R^B V_B \quad (2.35)$$

In terms of the direction cosines

$$C_R^B = \begin{bmatrix} C_{1X} & C_{1Y} & C_{1Z} \\ C_{2X} & C_{2Y} & C_{2Z} \\ C_{3X} & C_{3Y} & C_{3Z} \end{bmatrix} \quad (2.36)$$

To solve for these nine direction cosines the following equation, from Broxmeyer(1964), must be integrated

$$\dot{C}_R^B = C_R^B \Omega \quad (2.37)$$

where

$$\Omega = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \quad (2.38)$$

and all variables are functions of time.

Expanding equation (2.37) results in three sets of three differential equations

$$\begin{aligned}\dot{C}_{iX} &= C_{iY}\omega_3 - C_{iZ}\omega_2 \\ \dot{C}_{iY} &= C_{iZ}\omega_1 - C_{iX}\omega_3 \\ \dot{C}_{iZ} &= C_{iX}\omega_2 - C_{iY}\omega_1\end{aligned}\quad i = 1, 2, 3 \quad (2.39)$$

To determine the transformation matrix requires the integration of these nine equations. Since only four of the nine direction cosines are independent, computational errors in this integration may lead to a non-orthogonal matrix. This can be corrected by an iteration method which produces an orthogonal matrix through insuring that the sum of the squares of each row and column equal unity as described in Morris(1973). Therefore if direction cosines are used as the parameter set, nine equations must be integrated and an additional computation is required to orthogonalize the resulting transformation matrix.

If the quaternion set of parameters are used then

$$C_R^B = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1 q_2 - q_0 q_3) & 2(q_0 q_2 + q_1 q_3) \\ 2(q_0 q_3 + q_1 q_2) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2 q_3 - q_0 q_1) \\ 2(q_1 q_3 - q_0 q_2) & 2(q_3 q_2 + q_1 q_0) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix} \quad (2.40)$$

The solution for the quaternions (q_0, q_1, q_2, q_3) requires the integration of the following four differential equations from NASA CR-968

$$\begin{aligned}\dot{q}_0 &= -1/2(q_1\omega_1 + q_2\omega_2 + q_3\omega_3) \\ \dot{q}_1 &= 1/2(q_0\omega_1 + q_3\omega_2 - q_2\omega_3) \\ \dot{q}_2 &= 1/2(-q_3\omega_1 + q_0\omega_2 + q_1\omega_3) \\ \dot{q}_3 &= 1/2(q_2\omega_1 + q_1\omega_2 + q_0\omega_3)\end{aligned} \quad (2.41)$$

The quaternion parameters are based on Euler's theorem as stated in Greenwood(1965)

"The most general displacement of a rigid body with one point fixed is equivalent to a single rotation about some axis through that point."

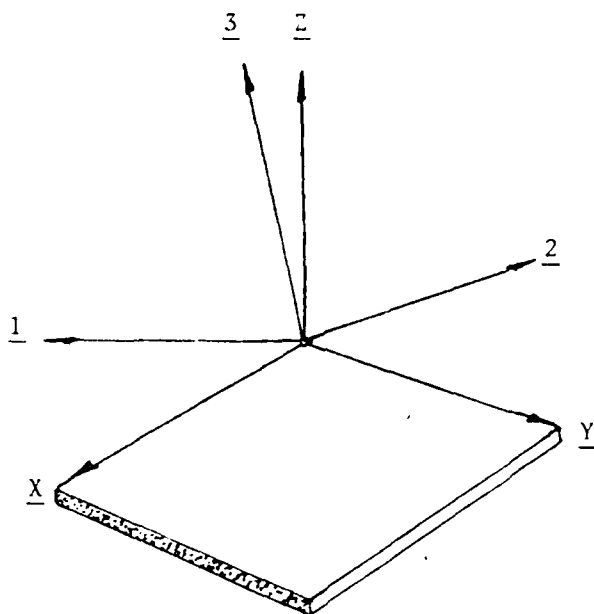


Figure 2-6. The Initial Arbitrary Orientation of the Body-Centered and Fixed Coordinate Systems.

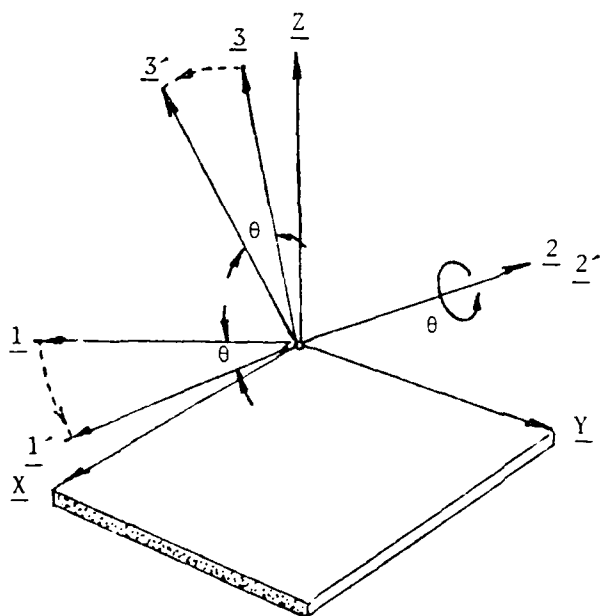


Figure 2-7. Rotation About the 2 Axis through Angle θ to Bring the 1 Axis into the XY Plane.

The four quaternians are composed of a unit vector which represents the axis about which the rotation occurs and a scalar which represents the magnitude of the angle of rotation. One of these variables is not independent and therefore the resulting transformation matrix must be orthogonalized as was done in the direction cosine parameter set. Therefore, if the quaternion set of parameters are used, four differential equations must be integrated and an additional computation to orthogonalize the transformation matrix is required.

If the Euler angle set of parameters are used, only three differential equations must be integrated and since all variables are independent, no additional computation to orthogonalize the transformation matrix is required as the resulting matrix is orthogonal. One additional advantage is the relative ease of relating the mathematical equations to the physical orientation of the coordinate systems. The principal disadvantage of the Euler angle set of parameters is that a singularity normally occurs in the mathematical equations. It will be shown that this presents no problem in this study. Because of the reduced computational requirements and the clear physical relationship between the mathematical equations and the orientation of the coordinate systems, the Euler angle set of parameters were used in this study. A complete derivation of the Euler angles will now be presented.

When Euler angles are used for the transformation from the body-centered system to the fixed system, three rotations are required to bring the two systems into alignment. An initial general orientation of the two systems is shown in Figure 2-6. The following rotations are used to bring the body-centered system into alignment with the fixed system

- (1) bring the 1 axis into the XY plane by rotating about the 2 axis through angle θ as shown in Figure 2-7.

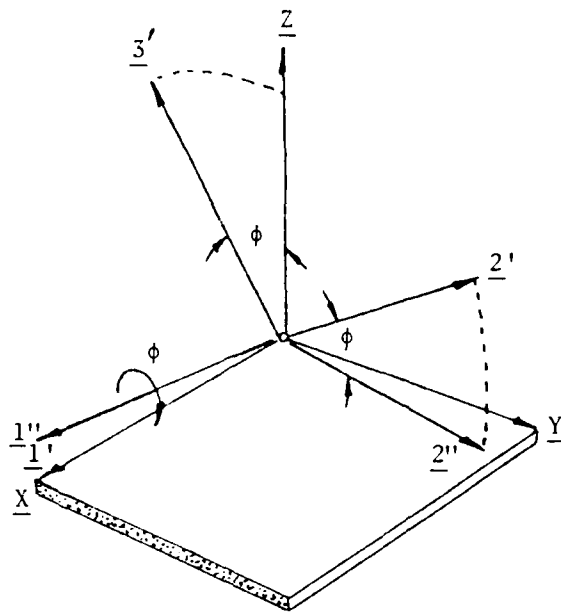


Figure 2-8. Rotation about the $\underline{1}'$ Axis through Angle ϕ to Align the $\underline{3}'$ Axis with the \underline{Z} Axis.

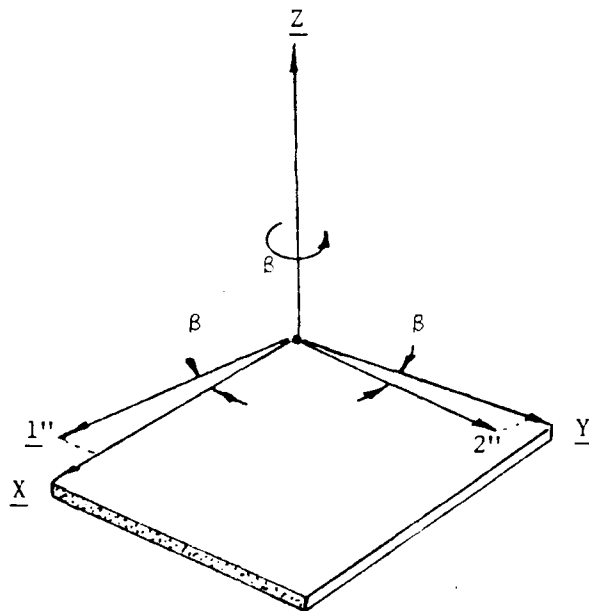


Figure 2-9. Rotation about the \underline{Z} Axis through Angle β to Complete the Alignment of the Body-Centered and Fixed Coordinate Systems.

- (2) bring the $\underline{3'}$ axis into alignment with the $\underline{2}$ axis by rotating about the $\underline{1'}$ axis through angle ϕ as shown in Figure 2-8.
- (3) complete the alignment by rotating about the $\underline{3''}$ axis through angle β as shown in Figure 2-9.

The single axis matrices corresponding to these rotations are

$$C_P^B = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \quad (2.42)$$

$$C_Q^P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix} \quad (2.43)$$

$$C_R^Q = \begin{bmatrix} \cos \beta & \sin \beta & 0 \\ -\sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2.44)$$

These matrices were developed from general coordinate rotations about a single axis as presented in Bate, Mueller and White(1971). The corresponding transformation matrix is given by

$$C_R^B = C_R^Q C_Q^P C_P^B \quad (2.45)$$

Carrying out the indicated matrix multiplication results in the transformation matrix

$$C_R^B = \begin{bmatrix} \cos \theta \cos \beta + \sin \theta \sin \phi \sin \beta & \cos \phi \sin \beta & -\sin \theta \cos \beta + \cos \theta \sin \phi \sin \beta \\ -\cos \theta \sin \beta + \sin \theta \sin \phi \cos \beta & \cos \phi \cos \beta & \sin \theta \sin \beta + \cos \theta \sin \phi \cos \beta \\ \sin \theta \cos \phi & -\sin \phi & \cos \theta \cos \phi \end{bmatrix} \quad (2.46)$$

Now differentiate equation (2.45) to obtain

$$\dot{C}_R^B = \dot{C}_R^Q C_Q^P C_P^B + C_R^Q \dot{C}_Q^P C_P^B + C_R^Q C_Q^P \dot{C}_P^B \quad (2.47)$$

Recalling that for orthogonal systems

$$C_B^R = C_R^{B^{-1}} = C_B^P C_P^Q C_Q^R \quad (2.48)$$

substituting equations (2.47) and (2.48) into equation (2.37) results in

$$\Omega = C_B^R \dot{C}_R^B = C_B^P C_P^Q C_Q^R \dot{C}_R^B + C_B^P C_P^Q C_Q^R \dot{C}_P^B + C_B^P C_P^Q C_Q^R \dot{C}_Q^B \quad (2.49)$$

or since $C_Q^R C_R^Q = C_P^Q C_Q^P = I$, the identity matrix

$$\Omega = C_B^P \dot{C}_P^B + C_B^P C_P^Q \dot{C}_Q^P + C_B^P C_P^Q C_Q^R \dot{C}_R^P \quad (2.50)$$

The products $C_m^S \dot{C}_S^m$ appearing in equation (2.50) can be obtained from equations (2.42), (2.43) and (2.44) by multiplying the derivative of the appropriate matrix by its inverse, thus

$$\Omega_\theta = C_B^P \dot{C}_P^B = \begin{bmatrix} 0 & 0 & \dot{\theta} \\ 0 & 0 & 0 \\ -\dot{\theta} & 0 & 0 \end{bmatrix} \quad (2.51)$$

$$\Omega_\phi = C_P^Q \dot{C}_Q^P = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\dot{\phi} \\ 0 & \dot{\phi} & 0 \end{bmatrix} \quad (2.52)$$

$$\Omega_\beta = C_Q^R \dot{C}_R^Q = \begin{bmatrix} 0 & -\dot{\beta} & 0 \\ \dot{\beta} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2.53)$$

Substituting equations (2.51), (2.52) and (2.53) into equation (2.50) results in

$$\Omega = \Omega_\theta + C_B^P \Omega_\phi C_P^B + C_B^P C_P^Q \Omega_\beta C_Q^B \quad (2.54)$$

Since Ω , Ω_θ , Ω_ϕ and Ω_β are all antisymmetric matrices and all single axis rotation matrices are orthogonal, the similarity transformation applies so that equation (2.54) can be rewritten in vector form as

$$\begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = \begin{pmatrix} 0 \\ \dot{\theta} \\ 0 \end{pmatrix} + C_B^P \begin{pmatrix} \dot{\phi} \\ 0 \\ 0 \end{pmatrix} + C_B^P C_P^Q \begin{pmatrix} 0 \\ 0 \\ \dot{\beta} \end{pmatrix} \quad (2.55)$$

Performing the matrix multiplications indicated in the second and third

terms results in

$$\begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = \begin{pmatrix} 0 \\ \dot{\theta} \\ 0 \end{pmatrix} + \begin{pmatrix} \cos\theta \dot{\phi} \\ 0 \\ -\sin\theta \dot{\phi} \end{pmatrix} + \begin{pmatrix} \sin\theta \cos\phi \dot{\beta} \\ -\sin\phi \dot{\beta} \\ \cos\theta \cos\phi \dot{\beta} \end{pmatrix} \quad (2.56)$$

The corresponding scalar equations are

$$\omega_1 = \cos\theta \dot{\phi} + \sin\theta \cos\phi \dot{\beta} \quad (2.57)$$

$$\omega_2 = \dot{\theta} - \sin\phi \dot{\beta} \quad (2.58)$$

$$\omega_3 = -\sin\theta \dot{\phi} + \cos\theta \cos\phi \dot{\beta} \quad (2.59)$$

Rearranging these equations results in the set of non-linear, first order differential equations for the Euler angles

$$\dot{\theta} = \tan\phi (\sin\theta \omega_1 + \cos\theta \omega_3) + \omega_2 \quad (2.60)$$

$$\dot{\phi} = \cos\theta \omega_1 - \sin\theta \omega_3 \quad (2.61)$$

$$\dot{\beta} = \sec\phi (\sin\theta \omega_1 + \cos\theta \omega_3) \quad (2.62)$$

The singularity mentioned previously occurs in equations (2.60) and (2.62). If the angle ϕ becomes either 90 or 270 degrees, then the right hand side of those equations becomes infinite. This will not be a problem in this study as the maximum angles expected for pelvic movement are on the order of ± 15 degrees. Therefore, at no time should the singularity be encountered during computation of actual walking data.

The rotation angles θ , ϕ and β can now be determined by integrating equations (2.60), (2.61) and (2.62) simultaneously since ω_1 , ω_2 and ω_3 can be computed using the results of section 2.3. The required transformation matrix is then computed from equation (2.46) and any vector can then be transformed from the body-centered system to the fixed system. The acceleration measured in the body-centered system must be transformed to the fixed system before it can be integrated to yield translational velocity and position information.

2.5 Derivation of the Translational Parameters

The translational parameters of interest in this study are the acceleration, velocity and position of the body-centered system relative to the fixed system. The origin of the body-centered system is a point fixed within the rigid body. Therefore if the translational parameters of the origin are known as a function of time the translational motion of the rigid body is also known.

From the layout of the accelerometers as shown in Figure 2-4 it is apparent that the accelerometer pairs have been placed symmetrically about the origin of the body-centered system. Therefore, in vector notation, the locations for each accelerometer within a pair are given by $\underline{\rho}$ and $\underline{\rho}'$ and because of the symmetry

$$\underline{\rho} = -\underline{\rho}' \quad (2.63)$$

For example, the locations of the accelerometer pair on axis 3 are given by

$$\underline{\rho} = d_{13}/2 \underline{3} [\text{accelerometer } \underline{a}_1] \quad (2.64)$$

$$\underline{\rho}' = -d_{13}/2 \underline{3} [\text{accelerometer } \underline{a}'_1] \quad (2.65)$$

Rewriting equation (2.4) for an accelerometer pair, then

$$\underline{a} = \ddot{\underline{R}} + \dot{\underline{\omega}} \times \underline{\rho} + \underline{\omega} \times (\underline{\omega} \times \underline{\rho}) + \underline{g} \quad (2.66)$$

$$\underline{a}' = \ddot{\underline{R}} + \dot{\underline{\omega}} \times \underline{\rho}' + \underline{\omega} \times (\underline{\omega} \times \underline{\rho}') + \underline{g} \quad (2.67)$$

Substituting equation (2.63) into equation (2.66) yields

$$\underline{a} = \ddot{\underline{R}} - \dot{\underline{\omega}} \times \underline{\rho}' - \underline{\omega} \times (\underline{\omega} \times \underline{\rho}') + \underline{g} \quad (2.68)$$

Now adding equations (2.67) and (2.68) one obtains

$$\underline{a} + \underline{a}' = 2\ddot{\underline{R}} + 2\underline{g} \quad (2.69)$$

or

$$\ddot{\underline{R}} = 1/2(\underline{a} + \underline{a}') - \underline{g} \quad (2.70)$$

The acceleration of the origin of the body-centered system $\ddot{\underline{R}}$ must be expressed in the fixed system before it can be integrated to yield velocity and position. The accelerations \underline{a} and \underline{a}' have been measured in the body-centered system and therefore they must be transformed to the fixed system before equation (2.70) is integrated. The transformation matrix is known and therefore the acceleration is given by

$$\underline{A} = C_R^B (\underline{a} + \underline{a}')/2 \quad (2.71)$$

The gravitational acceleration is given in the fixed system by

$$\underline{g} = -1 \underline{Z} \text{ (in g's)} \quad (2.72)$$

Therefore the acceleration of the body-centered origin expressed in fixed system coordinates is

$$\ddot{\underline{R}} = \underline{A} - \underline{g} \quad (2.73)$$

With the acceleration of the origin of the body-centered system determined the velocity is given by

$$\underline{V} = \int \ddot{\underline{R}} dt + \underline{V}_0 \quad (2.74)$$

A second integration yields the position of the origin of the body-centered system, thus

$$\underline{R} = \int \underline{V} dt + \underline{R}_0 \quad (2.75)$$

Using the methods developed in this and the preceding sections the rotational and translation motion of a rigid body can be completely determined from accelerations measured by four pairs of accelerometers located on the rigid body. The measurement equipment designed to convert this theory into practice will be presented in the next chapter.

CHAPTER 3

THE EXPERIMENTAL APPARATUS

- 3.1 Introduction
- 3.2 The Accelerometer
 - 3.2.1 Design Considerations and Specifications
 - 3.2.2 Design Analysis
 - 3.2.3 Fabrication and Testing
- 3.3 The Electronic Equipment
- 3.4 The Body Mounting Method
- 3.5 The Calibration Method and Equipment

3.1 Introduction

In this chapter a description of the measurement equipment developed during this research study is presented. A general description of the equipment is followed by a detailed outline of the design, fabrication and testing of the accelerometers produced during this study. The electronic equipment designed and constructed to operate the accelerometers is discussed and the method used to mount the accelerometers on the pelvis of the subject is presented. The chapter concludes with a description of the calibration method and equipment and a discussion of the methods used to ensure temperature stability during data collection.

The purpose of the measurement equipment was to measure, and store in the computer for further data processing, the outputs of the eight accelerometers worn by the subject. These outputs were in the form of analog voltage levels which were converted into digital form for storage in the computer. The stored values were then converted to acceleration values using the results of the calibration procedure. The method of calibration, data collection and storage, and data processing by the computer will be discussed in chapter 4.



Figure 5-1. Body Mounted Equipment on Walking Subject.

The accelerometers were located within an equipment package mounted on the pelvis of the subject as shown in Figure 3-1. This body mounted package is described more completely in section 3.4. A subminiature 15 way cable connects the body mount to the electronic equipment rack and serves to transfer electronic signals between these two sets of equipment. This cable is small and lightweight and does not interfere with the movement of the subject during walking.

The electronic equipment was housed in the electronic equipment rack located beside the PDP 11/34 computer and was connected to the computer with short cables. The electronic rack and computer are shown in Figure 3-2. The electronic rack contained the bridge circuits, power supplies, output amplifiers, filters and sum and difference amplifiers required to process the output signals from the accelerometers for input to the computer. The design of the components of the electronic rack is described in detail in section 3.3.

Before data collection from a subject could begin, it was necessary to temperature stabilize and calibrate the accelerometers contained in the body mount. This stabilization and calibration were accomplished using the calibration rig shown in Figure 3-3. The calibration procedure, a description of the calibration equipment and a discussion of the temperature stabilization procedure are presented in section 3.5.



Figure 3-2. PDP 11/34 Computer and Electronic Equipment Rack.



Figure 3-3. Body Mount on Calibration Rig.

3.2 The Accelerometer

In the following subsections the design criteria for the accelerometers which were built for use in this study are presented. The theoretical analysis on which the design was based and the fabrication and testing of the accelerometers are reported.

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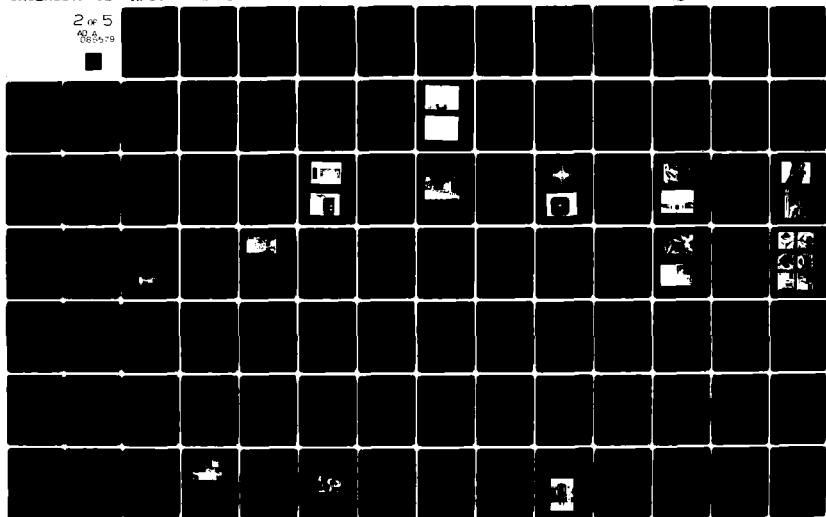
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3.2.1 Design Considerations and Specifications

The selection of a suitable accelerometer for this research involved determining the characteristics crucial to successful data acquisition. The criteria determined to be most important were small size, low weight, high sensitivity, low thermal drift and low cost. Based on preliminary estimates of the maximum expected acceleration values the accelerometer was required to have an operating range of ± 5 g's. The accelerometer had to be as small and light as possible in order to minimize the size and weight of the equipment to be attached to the pelvis of the subject.

The sensitivity and zero g offset of an accelerometer are measured, prior to collecting data, by a calibration procedure. The sensitivity, in volts/g, is determined by rotating the accelerometer about an appropriate axis so that the maximum and minimum output voltages are determined. The sensitivity is then determined from $(\text{maximum voltage} - \text{minimum voltage})/2$ as the maximum and minimum voltages correspond to the $+1$ g and -1 g positions in the gravitational field. Changes in the sensitivity may be caused by changes in the power supply voltage or temperature. With the stabilized power supply used in this study, the typical variation in sensitivity is 0.03%. The sensitivity also changes with temperature; a typical specification is $-0.3\%/^{\circ}\text{C}$ which indicates that the output of the accelerometer will decrease by 3% for every 10°C the temperature increases. These changes are small and not a serious cause for concern.

The major temperature effect is the variation in zero offset voltage which can result in serious errors during data acquisition. In Mitchell's research using accelerometers at the University of Strathclyde (1975) he found that cupping his hand over an accelerometer produced a zero shift of 0.15 g's in 7 minutes. This zero shift had not stabilized to a new value and immediately began to shift in the opposite direction when he removed his hand. Morris(1973) reported similar difficulties during the

calibration of his transducers. The solution in both cases was insulation of the transducers to minimize temperature changes between calibration and data acquisition. An accelerometer with low thermal zero shift must be used in order to minimize such difficulties.

In summary, the following accelerometer specifications were deemed essential to the successful completion of this research:

- (a) small size and low weight
- (b) operating range ± 5 g's
- (c) high sensitivity
- (d) low thermal zero shift
- (e) low cost.

A comprehensive search of commercially available accelerometers was made in 1975 for suitable accelerometers. The cantilever beam, strain gauge type of accelerometer construction was selected based on the size, weight and sensitivity requirements and a previous analysis by Morris(1973). Other types of construction, such as force-balance and piezoelectric crystal, did not meet one or another of the desired specifications. Since this particular use of accelerometers was relatively unusual, no commercial accelerometers were found which entirely satisfied the desired specifications. However, the Aksjeselskapet Mikro-Elektronikk(AME) Company of Horten, Norway had developed a silicon beam sensing element, the AE800 series, which they manufactured and used in producing accelerometers. The lowest operating range manufactured at that time was ± 75 g's. The specifications of this silicon beam and applications for measuring acceleration are contained in Appendix A.

As no suitable accelerometers were available from commercial sources, it was decided to design and build accelerometers for this study. The next section outlines the design analysis which was used.

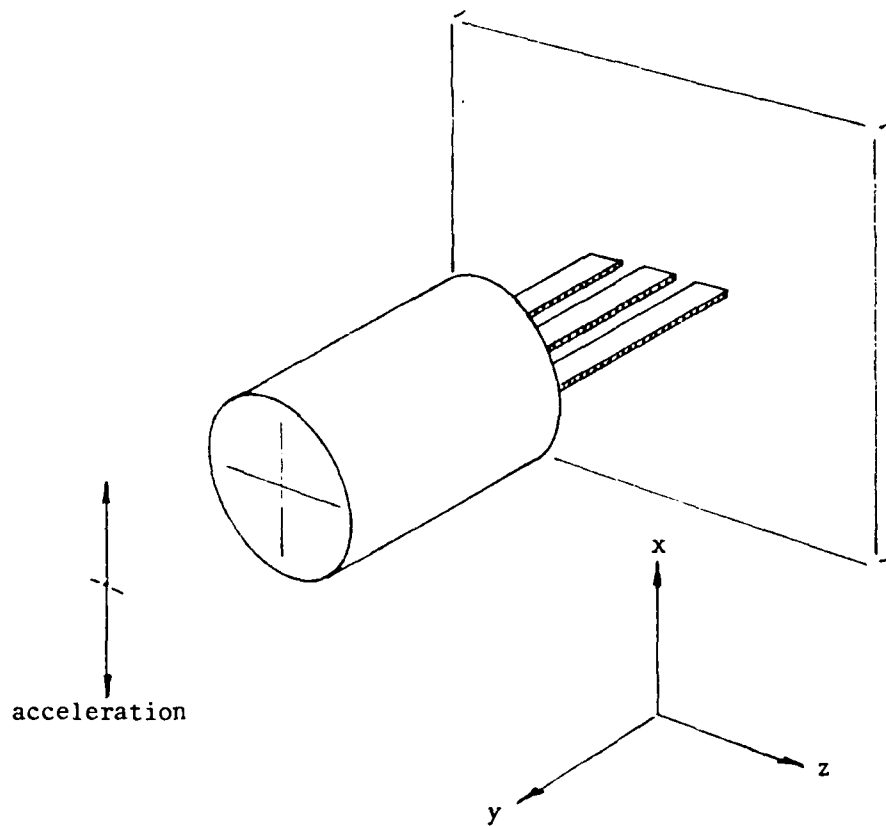


Figure 3-4. Cantilever Beam Accelerometer.

3.2.2 Design Analysis

The accelerometer design was based on drawings kindly supplied by the AME Company and consisted of a mass supported by a cantilever beam as shown in Figure 3-4. The cylindrical brass mass is supported by two beryllium copper beams on either side of the silicon beam sensing element. The design is primarily sensitive to accelerations in one direction (x) with minimal response to axial acceleration (y) or acceleration parallel to the plane surfaces of the beams (z-direction) since the beams stiffness is much greater in these directions. When the accelerometer undergoes an acceleration in the x direction a deflection of the beam is produced which is proportional to the applied acceleration for small deflections. The silicon sensing element has resistors diffused into the upper and lower surfaces such that when the beam deflects, putting one surface in tension and the other in compression, the change in resistance is proportional to the amount of deflection. More details of the structure and use of the silicon beam may be found in Appendix A.

The method used to analyze the deflection characteristics of the cantilever beam due to an applied load P, produced by an acceleration, was the double integration method. This is a common technique and is outlined in Higdon, Ohlsen and Stiles(1960). Using the variables and sign conventions shown in Figure 3-5, the moment equation is

$$EI \frac{d^2y}{dx^2} = Px - P(A + l/2) \quad (3.1)$$

where

E = modulus of elasticity of the beam

I = moment of inertia of the beam

P = the applied load

Integrating equation (3.1) yields

$$EI \frac{dy}{dx} = P(x^2/2 - Ax - lx/2) + C_1 \quad (3.2)$$

Applying the initial condition that at $x=0$ $dy/dx=0$, results in $C_1 = 0$. It

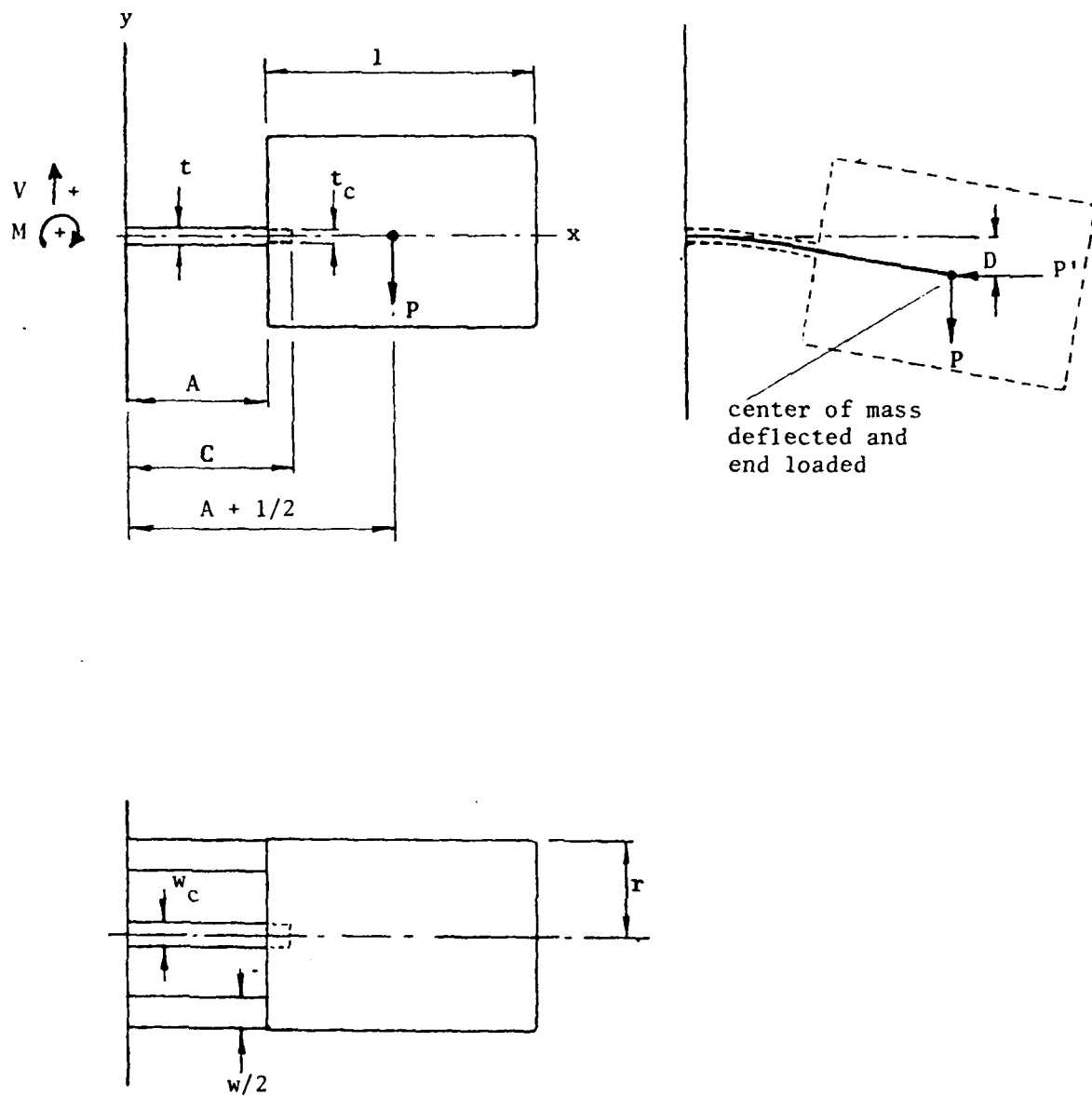


Figure 3-5. Accelerometer Design Variables.

is now possible to determine the slope of the deflected beam at point A (the base of the mass) from

$$dy/dx|_A = -PA(A + l)/2EI \quad (3.3)$$

Integrating equation (3.2) results in

$$EI y = P(x^3/6 - Ax^2/2 - lx^2/4) + C_2 \quad (3.4)$$

Now applying the initial condition that at $x=0$ $y=0$, results in $C_2 = 0$.

Thus, the deflection of the beam y at any point x (between $x=0$ and $x=A$) is given by

$$y = P(x^3/6 - Ax^2/2 - lx^2/4)/EI \quad (3.5)$$

Therefore the deflection of the end of the silicon beam, point C, is given by

$$y_C = y_A + dy/dx|_A(C - A) \quad (3.6)$$

It is assumed that the mass does not deflect internally and therefore the slope is constant over length l . Setting $x=A$ and substituting equation (3.5) and (3.3) into equation (3.6) results in

$$y_C = -PA(-A^2/3 - Al/2 + AC + lC)/2EI \quad (3.7)$$

The force P can be expressed as

$$P = am = a\rho_B r^2 l \quad (3.8)$$

where

a = the applied acceleration

m = mass of the brass cylinder

ρ_B = density of brass

r = radius of the brass cylinder

l = length of the brass cylinder

The stiffness of a single cantilever beam is

$$EI = E w t^3/12 \quad (3.9)$$

for a rectangular cross section, where

E = modulus of elasticity of beam material

w = beam width

t = beam thickness

Since the supporting beam is composed of two materials, beryllium copper and silicon, and the beams have different dimensions, the total stiffness is given by

$$EI = E_B I_B + E_C I_C \quad (3.10)$$

where

$E_B I_B$ = stiffness of the beryllium copper beam

$E_C I_C$ = stiffness of the silicon sensing beam

Using equations (3.7), (3.8), (3.9) and (3.10), it is now possible to determine the physical dimensions for a specific accelerometer operating range. The following variables are known from the mechanical properties of the beams and mass section and the desired operating range of the accelerometer:

a = maximum acceleration, $\pm 5 \text{ g} = \pm 49.0 \text{ m/sec}^2$

y_C = maximum end deflection of silicon beam, 0.1 mm

E_B = modulus of elasticity(beryllium copper),

$$1.186 \times 10^5 \text{ Newton/mm}^2$$

E_C = modulus of elasticity(silicon), $1.569 \times 10^5 \text{ Newton/mm}^2$

ρ_B = density of machine brass, $8.496 \times 10^{-6} \text{ kg/mm}^3$

w_C = width of silicon beam, 1.0 mm

t_C = thickness of silicon beam, 0.1 mm

C = length of silicon beam, 5.0 mm

The unknown variables are:

A = length of beryllium copper beam

w = width of beryllium copper beam

t = thickness of beryllium copper beam

r = radius of the brass cylinder

l = length of the brass cylinder

If values for A, w, t and r are selected, then l can be solved from a rearrangement of equation (3.7) which yields

$$l^2 + b l + d = 0 \quad (3.11)$$

where

$$b = (2/3)[(3AC - A^2)/(2C - A)]$$

$$d = 4EI_y / a\pi\rho_B r^2 A(2C - A)$$

The design process now involves:

- (1) selecting values for A, w, t and r
- (2) solving equation (3.11) for l
- (3) deciding if this solution produced acceptable sizes
- (4) if not, adjusting A, w, t and r until the sizes are acceptable.

To facilitate this design process a short program was written for a Hewlett Packard HP-20 computer. A listing of the program and sample results are contained in Appendix B. In addition to the dimensions of the accelerometer other accelerometer specifications are computed by this program and these will now be discussed.

In order to ensure that the elastic limit of the beryllium copper beam was not exceeded, the maximum stress occurring in the upper surface layer of the beam at the wall support was computed using

$$\sigma = P(A + 1/2)t/2I_B \quad (3.12)$$

The resonant frequency was computed from

$$f_n = (1/2\pi) \sqrt{3EI/[m(A + 1/2)]^3} \quad \text{in Hz} \quad (3.13)$$

This equation has been adapted from information given in Appendix A. The dynamic deflection due to a periodic acceleration of frequency f Hz is then

$$y_{\text{dynamic}} = y_C / [1 - (f/f_n)^2] \quad (3.14)$$

For this analysis it was assumed that the acceleration frequency was 2 Hz. The deflection difference due to dynamic deflection is given by

$$\Delta y = y_{\text{dynamic}} - y_C \quad (3.15)$$

This dynamic deflection must be small relative to the primary deflection as it represents an error in the output of the accelerometer.

Cross axis error is of major concern in accelerometer design. This error is the presence, in the output, of accelerations from directions other than the sensitive axis direction. In this design this error was primarily due to accelerations applied to the end of the beam. This acceleration produces a load P' which will increase any deflection present in the beam as shown in Figure 3-5. This cross axis error can be estimated using the double integration method.

If one assumes that the deflections are small and that the acceleration producing the load P' is approximately equal to that producing P so that $P = P'$, then equation (3.1) becomes

$$EI \, d^2y/dx^2 = P(x - A - 1/2 - D) \quad (3.16)$$

To estimate the maximum possible cross axis error, D was assumed to be

constant and equal to the maximum deflection possible, that is

$$D = y_A + dy/dx|_A l/2 \quad (3.17)$$

Integrating equation (3.16) and substituting equation (3.17) for D in the result produces the slope and deflection equations for the end loaded beam.

$$dy/dx|_A = -PA(A + 1 + 2y_A + dy/dx|_A l)/2EI \quad (3.18)$$

$$y_A = -PA^2(A/3 + l/4 + y_A/2 + dy/dx|_A l/4)/EI \quad (3.19)$$

The maximum deflection for the end loaded beam at point C can still be computed using equation (3.6). However, equations (3.18) and (3.19) require an iterative solution and when this is accomplished, the cross axis error can be computed from

$$\% \text{ cross axis error} = \frac{y \text{ (end loaded)} - y \text{ (no end load)}}{y \text{ (no end load)}} \quad (3.20)$$

The sensitivity of the accelerometer was computed using a rearrangement of an equation from Appendix A, thus

$$\Delta u/u = Pl't \lambda / 4EI \quad (\text{in mV/V}) \quad (3.21)$$

where

$l' = 3.0 + l/2$, the distance from the center of mass to the center of the diffused resistors

$\lambda = 60$, the gauge factor of the resistors

The term P/EI can be found in terms of the deflection y_C from equation (3.7)

$$P/EI \approx y_C/H \quad (3.22)$$

where

$$H = -A(-A^2/3 - Al/2 + AC + lC)/2 \quad (3.23)$$

The sensitivity per unit deflection was therefore

$$\Delta u/u/y_C = l't\lambda/4H \quad (3.24)$$

This sensitivity is normally specified per g of acceleration and in this case is given by

$$\Delta u/u/g = (l't\lambda/4H)(y_C/a) \quad (3.25)$$

where a maximum acceleration a (in g 's) produces a maximum deflection y_C (in mm).

To ensure an adequate clearance between the accelerometer housing and the suspended mass, the deflection of the end of the cylindrical mass must also be computed. This end deflection y_ℓ was calculated from

$$y_\ell = y_A + l \, dy/dx|_A \quad (3.26)$$

Using the analysis presented in this section, an accelerometer design was completed with the following theoretical specifications:

Operating range: ± 5 g's

Sensitivity: 4.2 mV/V/g

Cross axis sensitivity: < 3.5 % FS

Resonant frequency: 64 Hz

Non-linearity and hysteresis: < 1 % FS

Operating temperature range: -40 to +85° C

Nominal resistance: 1000 ohms

Resistance matching: < 10 %

Thermal sensitivity shift: -0.2 %/°C

Thermal zero shift: < 0.005 %/FSV/°C

Weight: 10 grams

A complete set of drawings for this accelerometer design are contained in Appendix C.

The preceding analysis was based on the cantilever beam and mass being surrounded by air. However, in most accelerometers the beam and mass are immersed in a viscous fluid to provide a slightly underdamped response. The viscous fluid increases the natural frequency of the device, which is desirable, but decreases the sensitivity which is undesirable. This decrease in sensitivity is normally of the order of 5-10 % which presents no problem.

The accelerometer designed in this study was filled with silicon fluid with a viscosity of 100 centistokes. This viscosity was arrived at experimentally by observing the frequency response of the accelerometers when filled with fluids whose viscosities were 23, 50 and 100

centistokes. Silicon fluid was selected because of the following features:

- (1) small variation in physical properties over a wide temperature range
- (2) relatively flat viscosity vs. temperature slope
- (3) good dielectric properties
- (4) low toxicity
- (5) no chemical reaction with most common materials.

The use of this fluid slightly reduced the sensitivity and produced the desired slightly underdamped response as will be shown in the testing section.

The fabrication and testing of the accelerometer designed using the preceding analysis will be discussed in the next section.

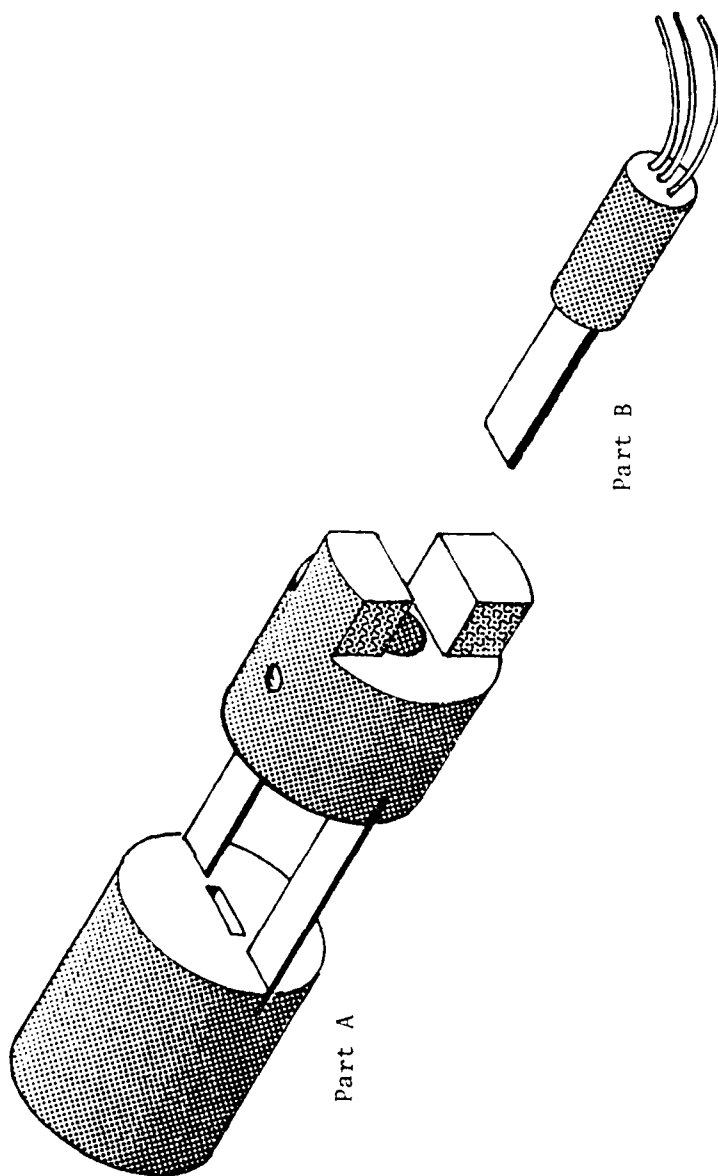


Figure 3-6. Accelerometer Internal Assembly.

3.2.3 Fabrication and Testing

The accelerometers designed using the analysis presented in the previous section were fabricated from the drawings contained in Appendix C. All components were machined from brass with the exception of the beryllium copper beam section and the screw which fits into the end of the accelerometer housing. This screw was a standard #2 BA steel grub screw from bench stock. The beam section was fabricated by machining an electrode of the specified shape. This electrode was then used in a spark erosion machine to spark erode the beam section from standard 0.006 inch beryllium copper shim stock. The individual beam sections were then annealed to maximum hardness.

The accelerometer was assembled by cementing the mount, beam and weight sections together using Araldite cement. This assembly was performed under a microscope to ensure proper alignment of these sections; the completed assembly is shown as Part A in Figure 3-6. After the cement was properly cured, the silicon beam sensing element, Part B in Figure 3-6, was inserted in the center hole of the mount, again using a microscope to ensure proper alignment. The end of the silicon beam was cemented to the weight and the silicon beam cylindrical header was cemented to the brass mount, again using Araldite.

The internal assembly was then inserted into the housing and secured in place with a #12 BA brass screw. The mounting end of the housing was then filled with silicon caulking compound to provide a seal. After curing, the accelerometer was then immersed in the silicon fluid with the open end of the accelerometer housing upward. The immersed accelerometers were then placed in a vacuum desiccator jar and evacuated to allow air bubbles to escape from the interior of the accelerometer. The evacuation process was repeated several times to ensure that no air remained trapped inside the accelerometer housing. The #2 BA grub screw was then installed

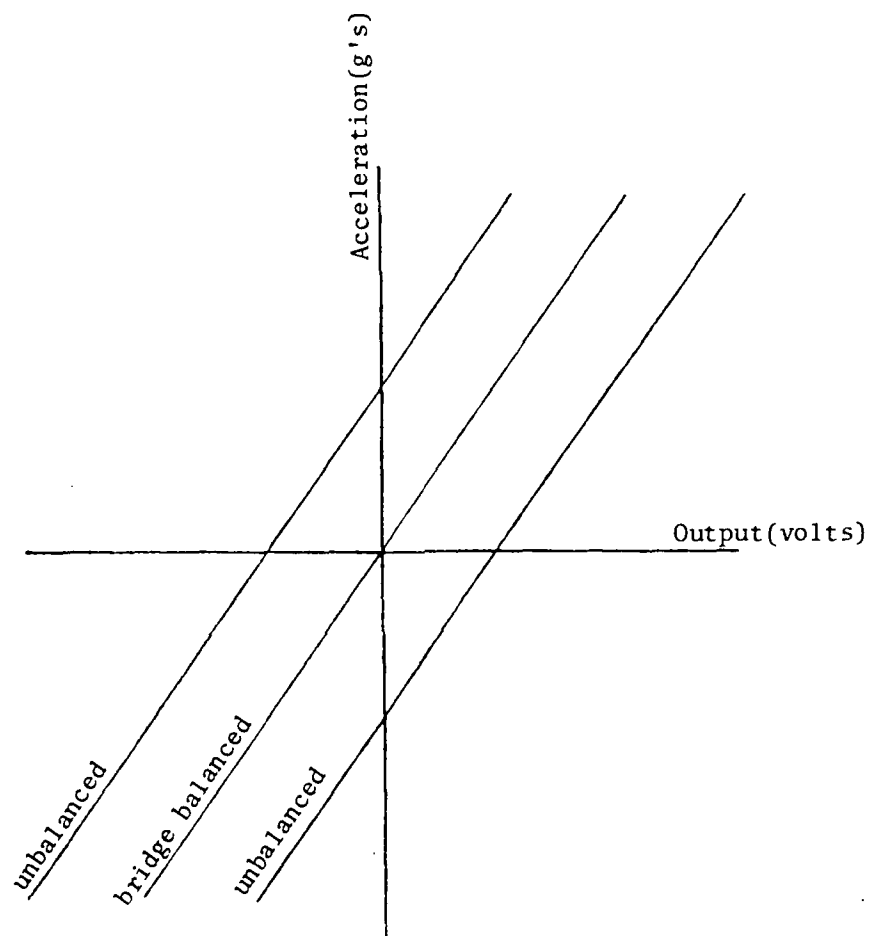


Figure 3-7. Typical Accelerometer Calibration Curves.

to seal the accelerometer housing. After fabrication and assembly the accelerometers were tested to determine their actual specifications.

An accelerometer was first mounted on a platform which allowed 360° rotation about a horizontal axis. The required resistance bridge and power supply, discussed in section 3.3, were used. A more complete calibration technique than used in these tests is presented in section 3.4. The 360° rotation corresponds to a change from +1 g to -1 g of acceleration. The sensitivity is computed using

$$\frac{\text{maximum voltage} - \text{minimum voltage} \quad (\text{mV})}{2 \text{ (g's)} \times \text{power supply voltage (volts)}} \quad (3.27)$$

The initial test results, with a supply voltage of 5.382 volts yielded a sensitivity of 4.16 mV/V/g which compares very favorably with the theoretical design value of 4.2 mV/V/g.

The cross axis sensitivity tests were made during calibration for data collection. During the calibration each accelerometer output would ideally be zero in four of the six calibration positions. The maximum output voltage for the four zero positions was assumed to be a measure of the maximum cross axis error for an accelerometer. The maximum cross axis error was then computed by dividing the maximum zero position voltage by the accelerometer full scale voltage. The mean cross axis error was 0.35 % FS with a maximum of 1.4 % FS and a minimum of 0.01 % FS. Therefore, the measured cross axis sensitivity specification is < 1.5 % FS which is less than one-half the design value.

The excellent linearity of resistive beams is well known and other authors have described in detail tests of accelerometer(transducer) linearity. In particular Mitchell(1975) has shown that even when the bridge and amplifier circuits are grossly out of balance, the calibration curve remains linear and merely shifts due to the out of balance condition as shown in Figure 3-7. However, a linearity test was performed for the

| Measured Angle (Deg) | Accelerometer Output (mv) | Measured Angle (After Offset Correction) (Deg) | Computed Angle (Deg) | Angular Difference (Deg) | Angular Sensitivity (mv/V/g) |
|----------------------|---------------------------|--|----------------------|--------------------------|------------------------------|
| -15 | 21.65 | -13.5 | -13.12 | -.38 | 4.137 |
| -10 | 22.00 | - 8.5 | - 8.25 | -.25 | 4.133 |
| - 5 | 22.19 | - 3.5 | - 3.44 | -.06 | 4.131 |
| + 1 | 22.20 | + 2.5 | + 2.98 | .48 | 4.129 |
| + 5 | 22.08 | + 6.5 | + 6.66 | .16 | 4.129 |
| +10 | 21.78 | +11.5 | +11.55 | .05 | 4.130 |
| +15 | 21.38 | +16.5 | +16.54 | .04 | 4.130 |

Supply Voltage = 5.382 Volts DC

Maximum Voltage Occured at $-1.5^{\circ} = 22.22 \text{ mV}$

Sensitivity (Computed from Maximum and = 4.132 mV/V/g
Minimum Voltages)

Table 3-I. Linearity Test Measurements

range $\pm 15^\circ$ about the $+1\text{ g}$ position. The resulting measurements and results are shown in Table 3-1. The angles were measured using a leveling protractor from a machinists combination set with an accuracy of $\pm 0.25^\circ$. The measured angles were corrected by subtracting the angle at which the maximum voltage occurred (-1.5°) as this position corresponds to the 0° position. The computed angles were determined by taking the inverse cosine of the measured voltage divided by the maximum voltage. The angular sensitivity was computed by dividing the measured voltage by the product of the cosine of the computed angle and the supply voltage. The deviation of the angular sensitivity from the calibrated sensitivity was used as a measure of the linearity of the accelerometer. The maximum deviation was 0.005 mV/V/g and therefore the linearity is better than 0.15% for the range tested. Thus, the design linearity specification of $< 1\%$ is valid. Comparing the angular differences between the measured and computed angles, the mean difference is 0.20° with a maximum value of 0.48° . It was concluded from this test that the accelerometer, when properly calibrated, can measure angles in the $\pm 15^\circ$ range about the $+1\text{ g}$ position to a typical accuracy of $\pm 0.2^\circ$ and with a maximum error of $\pm 0.5^\circ$.

The undamped natural frequency was determined by clamping the housing of an accelerometer which had not been filled with silicon fluid to a work bench and then exciting it by a sharp tap with a metal rod. The response was observed on a storage oscilloscope and then photographed. The resulting oscillation is shown in Figure 3-8. The period of the oscillation was approximately 0.0125 seconds which corresponds to a frequency of 80 Hz . The predicted frequency was 63 Hz and since a higher natural frequency was desirable, the measured natural frequency was better than design.

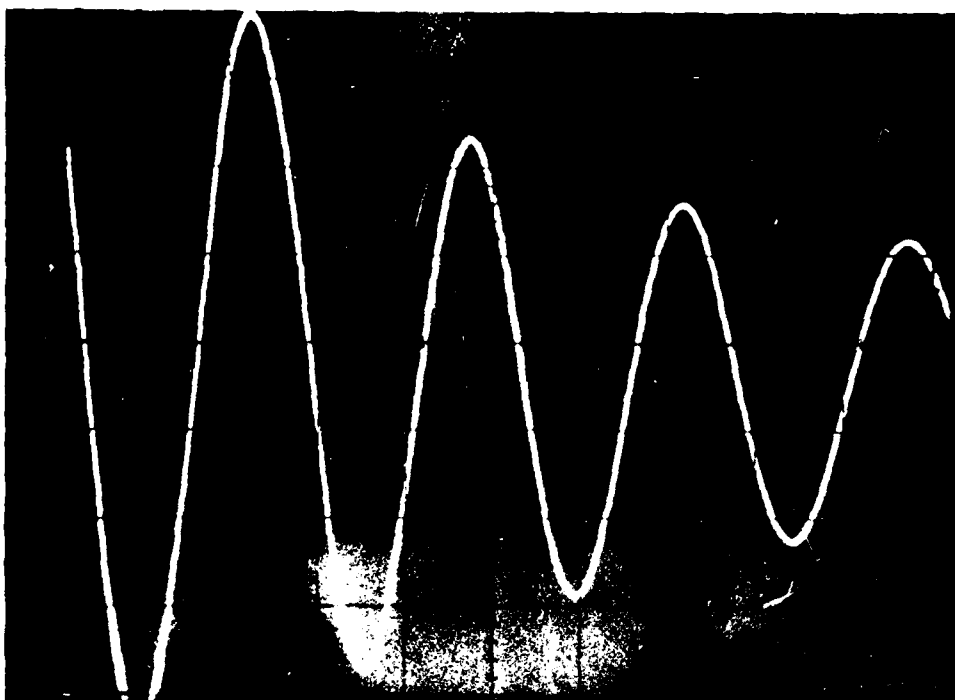


Figure 3-8. Undamped Accelerometer Response.
 Vertical scale: 2 volts/div
 Horizontal scale: 5 msec/div

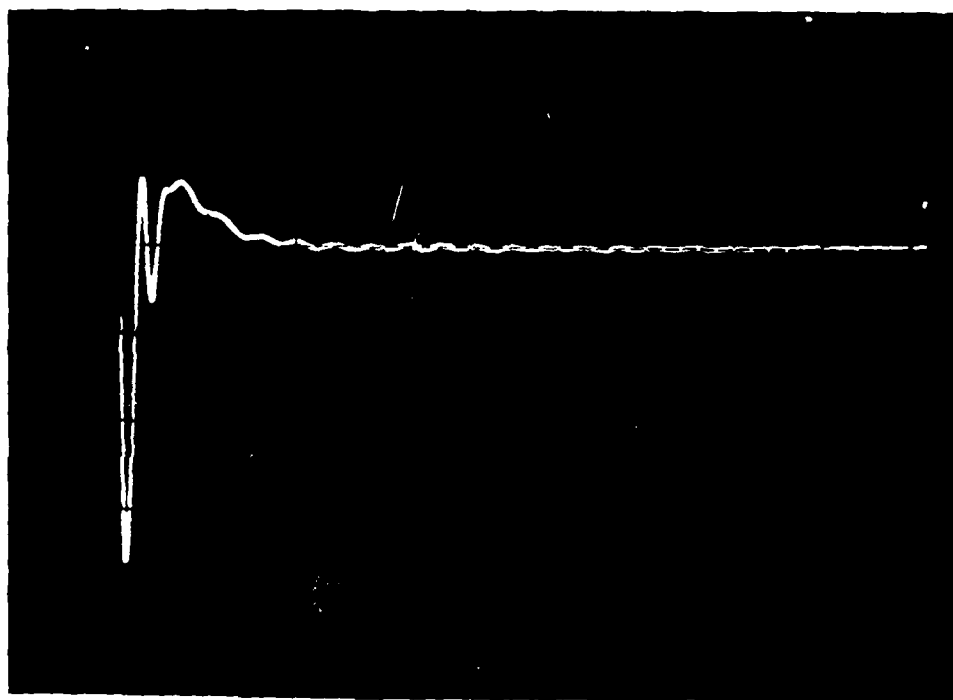


Figure 3-9. Damped Accelerometer Response.
 Vertical scale: 1 volt/div
 Horizontal scale: 5 msec/div

No attempt was made to determine quantitatively the exact damping ratio for an accelerometer filled with silicon fluid. However, response curves for a damped accelerometer were obtained to show that the response was slightly underdamped. A typical response to a sharp tap with a metal rod is shown in Figure 3-9 and is consistent with a damping ratio range of 0.5-1.0 which is the specified value.

In addition to the above tests, a check was made to ensure that the cylindrical masses suspended on the beam were of the proper weight. A total of 12 masses were weighed using a balance accurate to 10^{-4} grams. The mean mass was 2.339 grams with a standard deviation of 0.005 grams. The maximum deviation was 0.015 grams which corresponds to 0.65%. The design mass was 2.382 grams and therefore the actual mass exceeded the design value by 1.8%. This was much better than expected.

As indicated in section 3.2.1, one of the major problems with accelerometers used in this type of research has been zero shift due to temperature change. Extensive testing of thermal zero shift was performed under controlled conditions to determine accurately the thermal zero shift specification for these accelerometers. During this testing it became evident that a minimum warming period of 2 hours 45 minutes was necessary to stabilize the accelerometer output.

Thermal zero shift tests were conducted on nine accelerometers. The accelerometers were allowed to warm for a minimum of 3 hours at which time the initial temperature was measured and the accelerometers were calibrated. Using a controllable fan heater, described in section 3.5, the temperature was then raised and allowed to stabilize at which time the accelerometers were again calibrated to determine the zero offset voltage.

| Test Number | 1 | 2 | 3 | 4 | Avg. |
|---------------------------|-------------------------------|-------|-------|-------|-------|
| Temperature Range (°C) | 26-38 | 21-32 | 22-32 | 31-37 | |
| Accelerometer Number | Thermal Zero Shift (%/VFS/°C) | | | | |
| 1 | .039 | .040 | .029 | .028 | 0.034 |
| 2 | .006 | NT | .008 | .013 | 0.009 |
| 3 | .002 | .001 | .009 | .001 | 0.003 |
| 4 | .001 | .002 | .001 | .001 | 0.001 |
| 5 | .004 | NT | NT | NT | 0.004 |
| 6 | .005 | .007 | .007 | .005 | 0.006 |
| 7 | .007 | .005 | .003 | .001 | 0.004 |
| 8 | .001 | .0003 | .0005 | .001 | 0.001 |
| 9 | NT | NT | NT | .034 | 0.034 |

Note: NT indicates no test, only 8 accelerometers could be tested at one time.

Table 3-II. Thermal Zero Shift Test Results

The thermal zero shift was then computed using

$$\text{thermal zero shift} = \frac{V}{VFS \times VPS \times \Delta T} \times 100\% \text{ (\%/VFS/}^{\circ}\text{C)} \quad (3.28)$$

where

V = measured voltage change (volts)

VFS = full scale voltage range (volts)

VPS = power supply voltage (volts)

ΔT = temperature change ($^{\circ}\text{C}$)

The temperature changes and resulting thermal zero shifts are shown in Table 3-II. Five of the nine accelerometer zero shifts were less than the design specification of 0.005 %/VFS/ $^{\circ}\text{C}$. One accelerometer exceeded the specification by 20 %(number 6), one exceeded it by 80 %(number 2) and two exceeded it by 580 %(numbers 1 and 9).

Zero shift can be caused not only by temperature change, but also by mechanical means within the accelerometer support system. Two possible causes are mechanical movement of the cantilever beam assembly during the calibration procedure due to a loose fit between the accelerometer housing and the cantilever beam mount or relative movement between the beryllium copper beams and the silicon beam sensing element. There are other possible mechanical causes none of which can be accurately assessed as internal movement cannot be detected. Therefore, it was concluded that the large zero shift of accelerometers 1 and 9 were due to unknown mechanical problems and not to temperature changes. With the proper control of the temperature of the apparatus, as discussed in section 3.5, the effects of this anomalous thermal sensitivity were reduced to acceptable levels.

If the zero shifts of accelerometers 1 and 9 are omitted, the mean zero shift due to temperature change was 0.004 %/VFS/ $^{\circ}\text{C}$. Therefore, it was concluded that the design specification of < 0.005 %/VFS/ $^{\circ}\text{C}$ was accurate. This zero shift can also be expressed as 0.0005 g's/ $^{\circ}\text{C}$. These

Operating range: ± 5 g's
Sensitivity: 4 mv/v/g
Cross axis sensitivity: $<1.5\%$ FS
Resonant frequency: 80 Hz
Non-linearity and hysteresis: $<1\%$ FS
Operating temperature range: -40 to $+85$ °C
Nominal resistance: 1000 ohms
Resistance matching: $<10\%$
Operating voltage: 10 Volts (maximum)
Thermal sensitivity shift: $-0.2\%/^{\circ}\text{C}$
Thermal zero shift: $<0.005\%/^{\circ}\text{C}$
 or <0.0005 g's/ $^{\circ}\text{C}$
Damping: 0.7 - 1.0
Weight: 10 grams

Figure 3-10. Accelerometer Specifications.

thermal zero shift measurements are total system shifts including the drift of the electronic bridge circuits, amplifiers, filters and the analog to digital converter as the specifications were computed from voltages stored in the PDP 11/34 computer using the calibration program. The effect of this zero shift on calibration and data reduction will be discussed in chapter 4.

The verified specifications for the accelerometer are shown in Figure 3-10. The electronic equipment required to operate the accelerometers and process their output signals for storage in the PDP 11/34 computer will be presented in the following section.

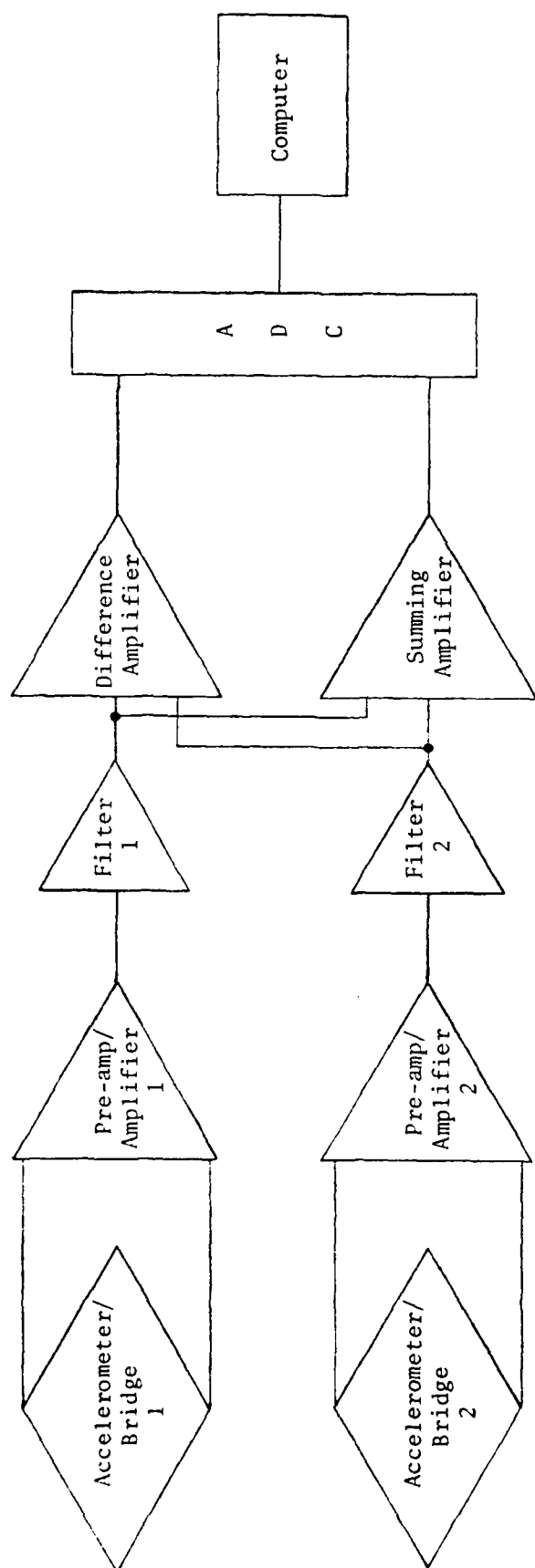


Figure 3-11. Electronic Equipment Signal Flow Diagram.

3.3 The Electronic Equipment

The electronic equipment required to operate the accelerometers and process output signals for storage in the PDP 11/34 computer is shown in Figure 3-11. The accelerometer and bridge output signals were amplified to a voltage level suitable for input to the analog to digital converter(ADC). To reduce high frequency noise, which may be present in the output, the signal was then filtered. As discussed in chapter 2, the outputs of accelerometer pairs must be added and subtracted in the computation of the rotational and translational parameters. Therefore, sum and difference amplifiers were provided to input these signals directly to the ADC. The digital output from the ADC was then stored on the magnetic disc of the computer for further processing and analysis. The ADC resolution was 1 part in 1024, or 0.098 % of full scale input; in this case the full scale input voltage was 4.99 volts and the resolution was 5 millivolts. The primary design criteria for the electronic equipment was to keep the errors in the output level below that of the ADC.

The sensing element of the accelerometers was a 1/2 resistive bridge. In order to produce an output voltage proportional to the sensed acceleration the accelerometer must be connected to a voltage supply and a second 1/2 resistive bridge to form a full Wheatstone bridge network. The complete bridge circuit is shown in Figure 3-12. The bridge circuit was composed of body mounted components, the accelerometers and zener diode, and electronic rack components, bridge resistors and potentiometers and voltage supply, with an interconnecting cable. The 200 ohm dropping resistors were used to reduce the supply voltage of ± 15 VDC to approximately ± 3.2 volts for the zener diode. The bridge was powered by a ± 15 volt stabilized power supply identical to the amplifier power supply which will be discussed later in this section. It was essential that a stable voltage be supplied to the bridge as any change in the bridge

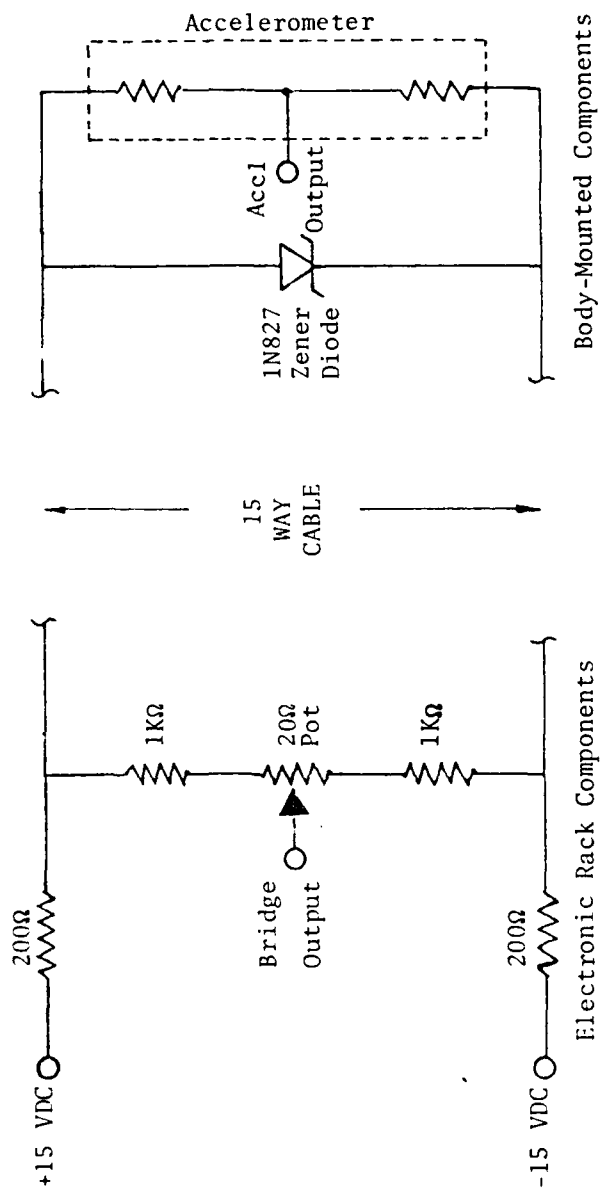


Figure 3-12. Accelerometer and Bridge Circuit.

voltage would produce a change in the sensitivity from the calibrated value. Therefore, a 1N827 zener diode was included in the bridge circuit to stabilize the bridge voltage. This diode provided a stable voltage of 6.2 VDC ± 5 % and was temperature compensated with a temperature coefficient of 0.001 %/°C.

The 1K ohm resistors which form the second 1/2 resistive bridge are shown on the left of Figure 3-12. These were not physically individual resistors as shown but were packaged thin film resistance chips which were selected to minimize thermal drift in the bridge circuit. The resistances contained in each chip are matched to within ± 1 % and have a maximum tracking temperature coefficient of ± 2 ppm/°C. This tracking corresponded to a zero drift of 0.0002 %/°C which is significantly smaller than the accelerometer thermal zero drift. To calibrate the bridge circuit properly, a means of balancing the bridge to zero output in a null position was necessary. This was accomplished by locating a 20 ohm, 15 turn cermet potentiometer in the 1/2 resistive bridge. This potentiometer allowed the bridge to be balanced accurately prior to calibration in order to maintain the zero offset value at approximately zero volts.

Several input amplifier designs were considered for use, including relatively expensive chopper stabilized amplifiers, in order to minimize amplifier drift. In addition to low drift a high common mode rejection ratio (CMRR) was desirable to minimize the effect of bridge supply variation. The amplifier circuit chosen was a low drift operational amplifier design contained in the LM321A precision preamplifier specification which is shown in Appendix D. This preamplifier contained a provision for nulling offset voltages and had a thermal drift of less than $1 \mu\text{V}/^\circ\text{C}$ when nulled. The resistors in the preamplifier were selected to ensure matching to better than 0.02% to give a CMRR in excess of 70 dB. The preamplifier was coupled to an LM308A operational amplifier which had

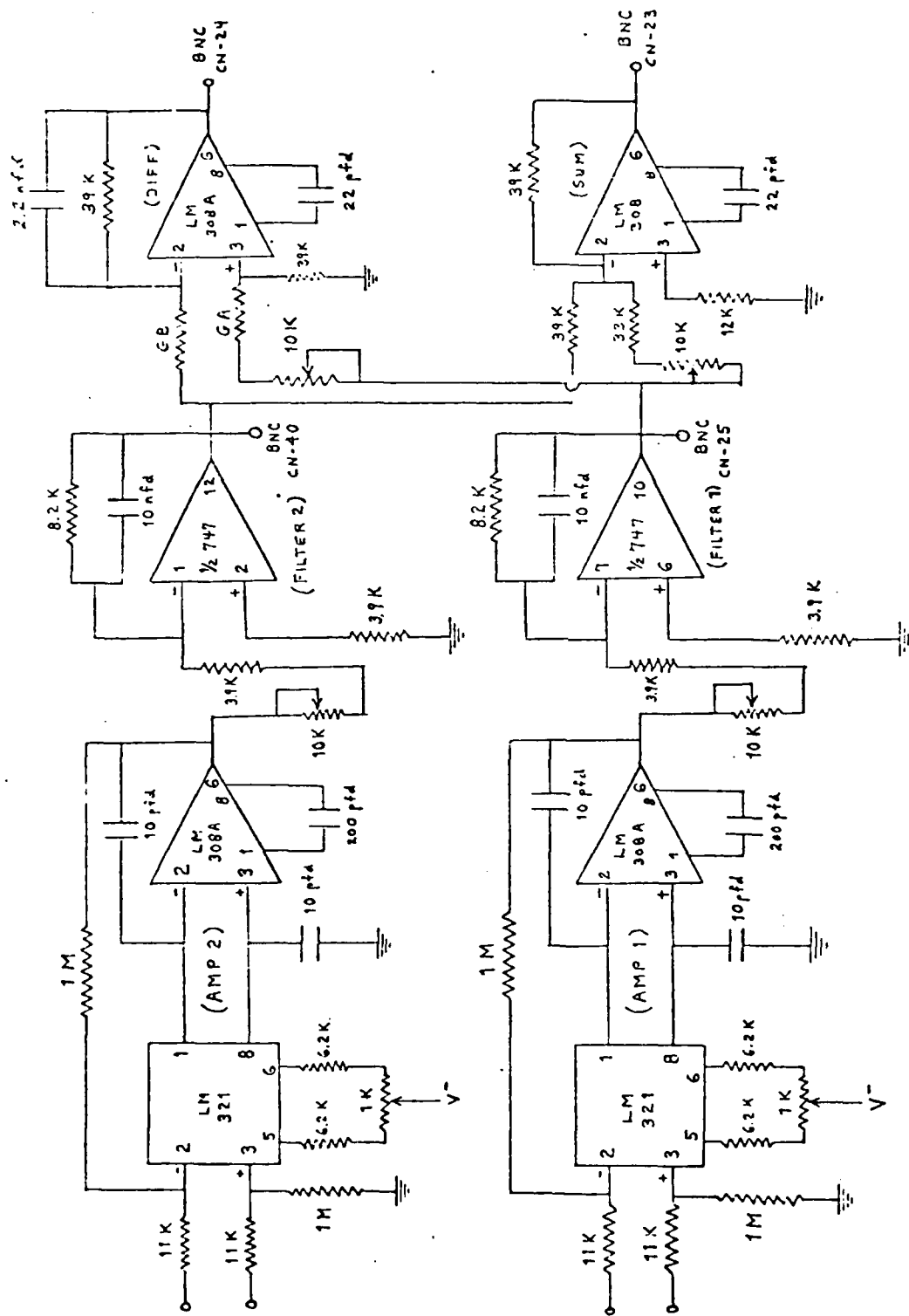


Figure 3-13. Schematic Diagram of Amplifier/Filter Circuits.

a typical drift of $1 \mu\text{V}/^{\circ}\text{C}$ and a maximum guaranteed drift of $5 \mu\text{V}/^{\circ}\text{C}$. The specification sheets for the LM308A are also contained in Appendix D.

The gain of the output amplifier was made adjustable by using a 10 K ohm potentiometer as a voltage divider in the output. This allowed the gain to be adjusted from approximately 55 to 190. The input from the accelerometer bridge circuit was 25 mV/g and therefore the maximum amplifier output was 4.75 volts/g which was more than sufficient to provide the proper input voltage to the ADC and the computer.

In order to minimize high frequency noise signals, a filter was added to the output side of the amplifiers. The filter was designed for a cutoff frequency of 4 KHz which did not result in any loss of information as the data had a fundamental frequency of 2 Hz and was sampled at a rate of 200 Hz. The preamplifier, amplifier and filter circuits are shown in Figure 3-13.

The difference signals from accelerometer pairs could be obtained by subtracting individual accelerometer outputs after they have been stored in the computer. However, it was expected that the difference signals would be much smaller than the accelerometer signals since the rotational components comprised only 20-30 % of the basic signal. Digital subtraction would therefore decrease the resolution from 1 part in 1024 to approximately 1 part in 250. Therefore, differencing was produced by amplifiers as shown in Figure 3-13. Additional signal gain, from 3.0 to 4.74, was provided by these amplifiers to accommodate particular accelerometer pairs. These gains were selected by recording test data and then adjusting the gain to an optimum value for input to the ADC.

Summing amplifiers were also included to provide accelerometer pair sums to the computer. These amplifiers were designed with unity gain. Both the summing and difference amplifiers contained 10 K ohm potentiometers in the input line from the second accelerometer of a pair to balance the gain

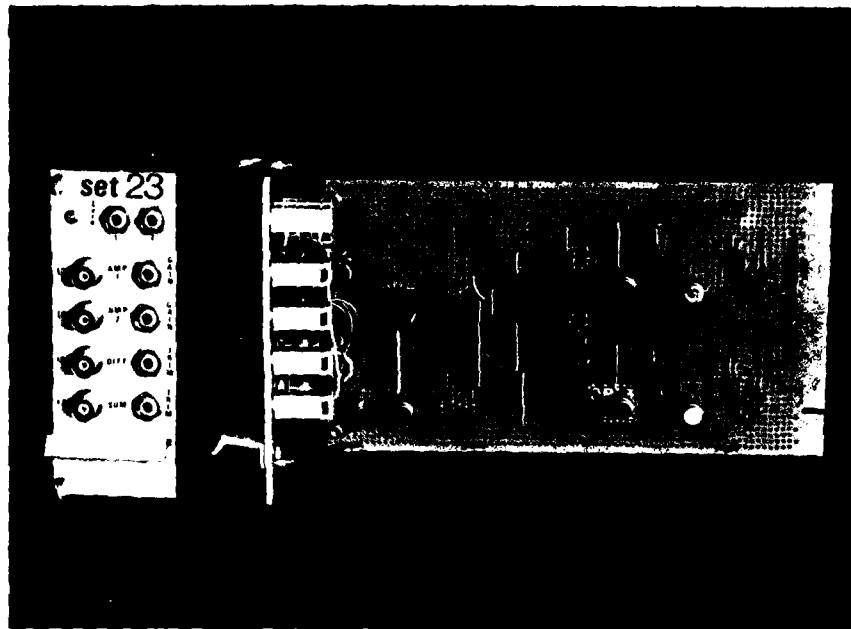


Figure 3-14. Accelerometer Pair Circuit Board(front and side view).

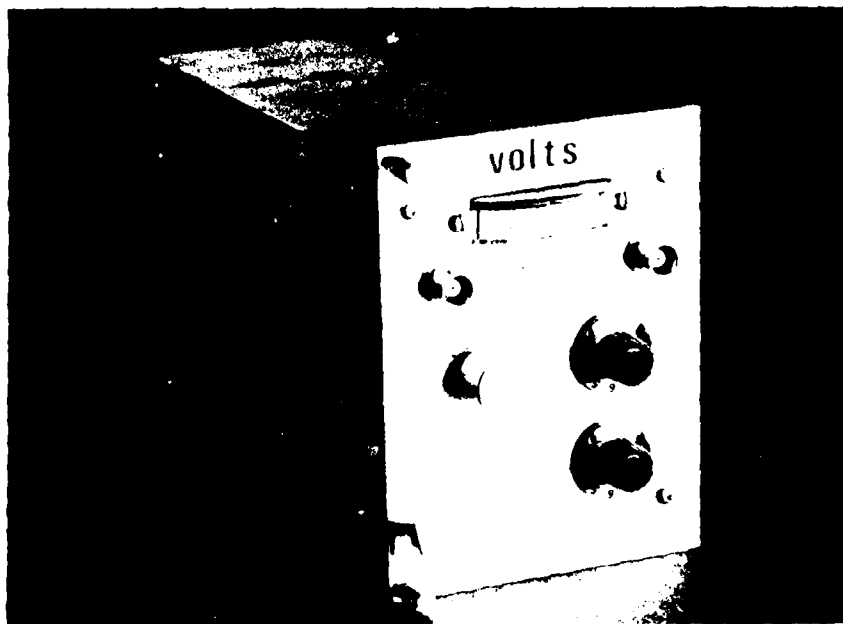


Figure 3-15. Electronic Equipment Rack Voltmeter.

of these amplifiers.

The electronic circuits were constructed so that one circuit board contained all the components necessary to operate one pair of accelerometers except the bridge circuits which were placed on a separate circuit board. The circuit board for one pair of accelerometers is shown in Figure 3-14. The circuit diagram equivalent to one circuit board, Figure 3-13, also shows the two preamplifiers, two amplifiers, two filters and the one sum and one difference amplifier required for each of the accelerometer pairs.

Two ± 15 VDC stabilized power supplies were constructed; one for the bridge circuit and a second for the amplifiers. Both were dual regulated with a potentiometer to balance the positive and negative output voltages to equal levels. These power supplies were constructed from standard designs and complete specifications and circuit diagrams are contained in RS Components Limited circular R/2040 a copy of which is provided in Appendix E.

The gain and zero of the amplifiers had to be balanced initially and at periodic intervals. To facilitate this a voltmeter, shown in Figure 3-15, was constructed. The voltmeter also provided the capability to monitor the output signals during calibration, testing and data acquisition to ensure proper signal levels. The amplifier balancing procedure required a signal generator to provide simulated input signals and a dummy load box of fixed resistance values to simulate the bridge circuit and accelerometers. The electronic rack with the dummy load box installed is shown in Figure 3-16. With the dummy load box installed and no input, the output of each of the eight accelerometer amplifiers was adjusted to zero volts using the individual offset potentiometer for each accelerometer amplifier. The dummy load box was removed and the signal generator, set to produce a peak-to-peak signal of 40 mV at 2 Hz, was

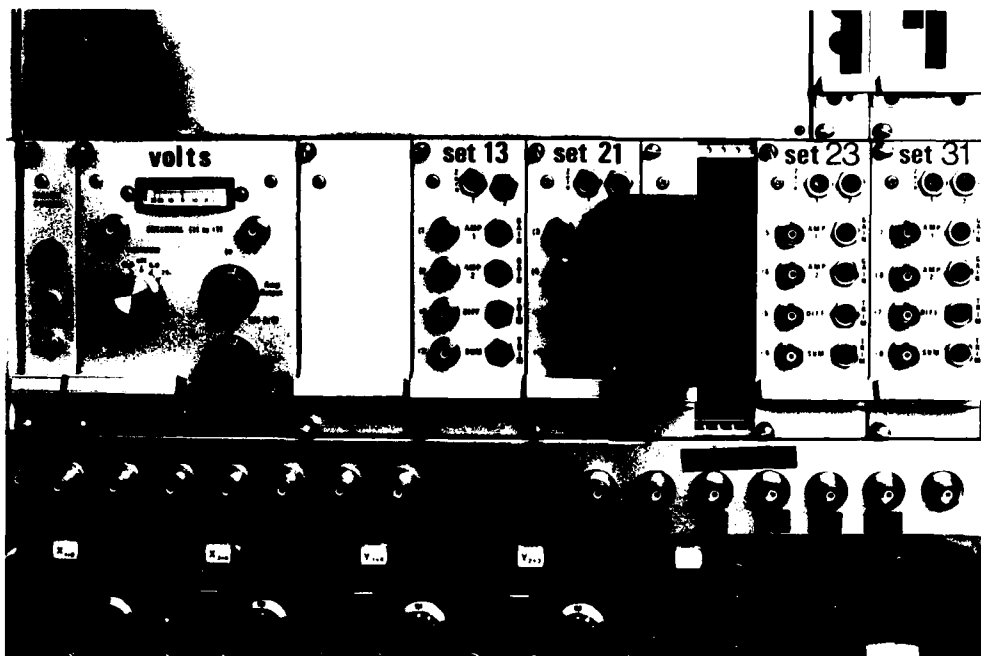


Figure 3-16. Electronic Rack with Dummy Load Box Installed.

connected to the input of all eight accelerometer amplifiers using a cable adapter. The gains of each pair of accelerometers were set to a predetermined identical value by adjusting the gain potentiometers. The output of the difference amplifiers was then adjusted to a minimum value using the trim potentiometer. This completed the amplifier balancing procedure. The summing amplifiers were balanced during the initial calibration procedure by insuring that the voltage output by the summing amplifiers was equal to the sum of the voltage outputs of the individual accelerometer amplifiers for each pair. The dummy load box was used to test the CMRR of the amplifier. An 8 volt, 2 Hz signal was applied to both preamplifier inputs and the CMRR, under these conditions, was determined to be in excess of 100 dB.

The electronic equipment and accelerometers which must be mounted on the pelvis of the subject and the mounting method are discussed in the next section.

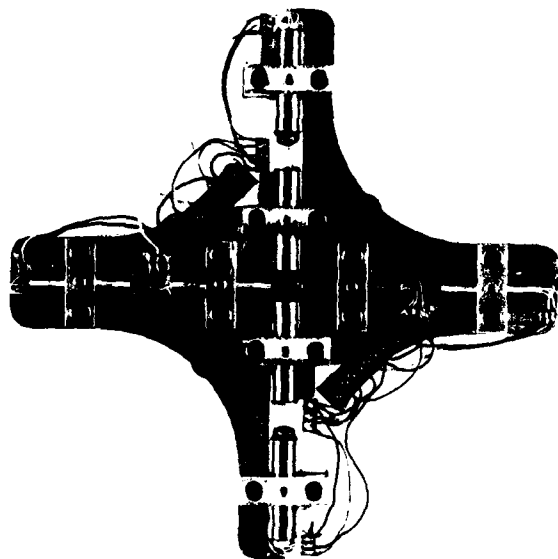


Figure 3-17. Accelerometer Mounting Platform.

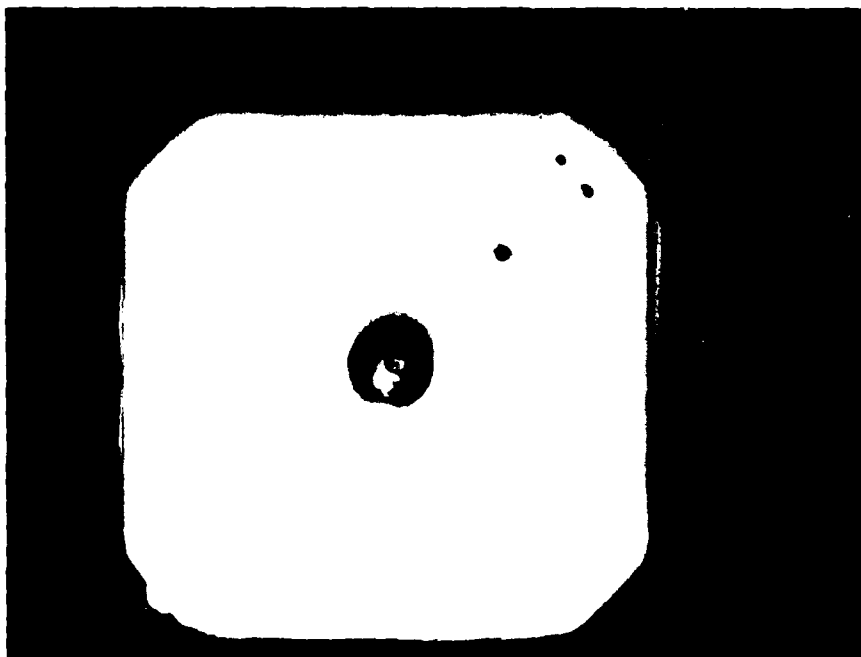


Figure 3-18. Accelerometer Platform with Cover Installed.

3.4 The Body Mounting Method

In order to measure the accelerations of the pelvis during walking an equipment package, the body mount, had to be securely attached to the pelvis of the subject. The body mount had to contain all essential equipment, be as small and lightweight as possible and be attached to the subject in a manner which did not interfere with normal walking motion. The accelerometers also had to be fixed securely in the proper configuration in order to measure the necessary accelerations.

The platform for mounting the eight accelerometers was fabricated in a cruciform shape from aluminum as shown in Appendix C. Channels were milled into the surface to accept the cylindrical accelerometers and pins were located in the channels to ensure exact placement of the accelerometers. A second drawing in Appendix C shows the brackets used to secure the accelerometers in the correct position. To provide the necessary electrical and mechanical connections, two centrally located socket connectors were mounted on the aluminum platform. The completed platform, with accelerometers in place, is shown in Figure 3-17.

A covering box of aluminum sheet was fabricated which contained the zener diode and two central pin connectors which mated with the socket connectors on the platform. The pin connectors were wired to the 15 way cable which was clamped to the covering box and carried the electronic signals to the electronic rack. The covering box was encased in 1/4 inch foamed polystyrene to provide thermal insulation and was secured mechanically to the platform by mating the central pin and socket connectors. A 1 1/2 inch diameter steel ball was mounted on the exterior of the covering box. The accelerometer platform with the covering box in place is shown in Figure 3-18.



Figure 3-19. Orthoplast Pelvic Mount.



Figure 3-20. PTFE Cup and Belt Holder.

This accelerometer equipment package must be attached securely to the pelvis. The site selected for attachment was just over the sacrum above the gluteal fold and below the L5-S1 articulation. A Y-shaped piece of 1/8 inch thick Orthoplast was molded to the shape of the sacrum on two subjects, one male one female. The Orthoplast is easily moulded when slightly heated and retains the desired shape when cooled. It was carefully moulded and trimmed to ensure that the primary contact with the subject was over the sacrum and there was no interference caused by the gluteal muscles.

The shaped Orthoplast mount was then secured to the rear of the accelerometer platform with machine screws. Two layers of shaped Plastazote, one tapered softwood wedge and 1/4 inch of foamed polystyrene were interposed to provide thermal insulation from body heat and maintain a near vertical alignment of the body mount when attached to a subject. The Orthoplast mount attached to the accelerometer platform is shown in Figure 3-19.

The completed body mount was attached to the sacrum of the subject in order to measure the accelerations of the pelvis during walking. The steel ball provided a means of forcing the body mount firmly against the sacrum while allowing complete freedom of movement. To provide the mounting force, a spherical cup of PTFE was machined to mate with the steel ball and secured to an aluminum belt holder. Two web belts with velcro fasteners were threaded into the belt holder as shown in Figure 3-20.

The body mount was secured to the sacrum of the subject by placing the PTFE cup on the steel ball and securing the web belts around the subject. One belt was passed below the iliac crests and the other above as shown in Figure 3-21. The belts pressed the body mount firmly against the sacrum and provided a satisfactory method of securing the body mount to



Figure 3-21. Body Mount Attached to Subject.



Figure 3-22. Subject in Pelvic Fixing Apparatus.

the pelvis and sacrum. This method of securing the belts above and below the iliac crests was also used at the University of Iowa to secure accelerometers in studies by Robinson(1972) and Smidt, et.al.(1971 and 1977).

The relative movement of the body mount was closely observed and it appeared that, if the device was properly mounted, it did move with the pelvis with little or no extraneous motion. An attempt was made to qualitatively evaluate the effectiveness of the attachment method. A subject was placed in an apparatus which securely fixes the position of the pelvis as shown in Figure 3-22. Loads of 1, 2, 3, 4 and 5 pounds were applied to the body mount in the horizontal and vertical directions and the distance the body mount moved was recorded. The maximum acceleration measured during walking was equivalent to an applied load of 18 Newtons(up and down 4 pounds-force) with a corresponding measured peak to peak position of 6.5 cm. The static loading resulted in a peak to peak movement of 4.5 mm. Therefore, it was estimated that the errors due to relative movement between the body mount and pelvis were less than 5 %.

Prior to mounting the accelerometer body mount on the subject, it must be calibrated. The calibration method and equipment will now be discussed.

3.5 The Calibration Method and Equipment

In order to calibrate an accelerometer it must be mounted with the sensitive axis in the vertical plane and then rotated about a horizontal axis through positions which correspond to +1 g and -1 g. By recording the output voltage corresponding to these positions the accelerometer can easily be calibrated. As stated in section 3.2.3, the calibration function is linear and can be expressed as

$$G = S_F V + B \quad (3.29)$$

where

G = acceleration in g's

S_F = scaling factor(slope) in g's/volt

V = output voltage in volts

B = offset from zero in g's

It is desirable, but not essential, to maintain the offset as close to a null value as possible. This was accomplished by adjusting the bridge circuit potentiometer to a null output when the accelerometer was in a "zero g" position.

The scale factor and offset were computed from the +1 g and -1 g voltage measurements as follows:

(1) compute S_F using

$$S_F = \frac{2 \text{ g's}}{V[+1 \text{ g}] - V[-1 \text{ g}]} \quad (\text{in g's/volt}) \quad (3.30)$$

(2) select the reference offset position (normally 0 g)

(3) compute B using

$$B = G - S_F V \quad (3.31)$$

where

G = 0, +1, or -1 as appropriate

V = the corresponding measured voltage

| | | Accelerometer Number | | | | | | | |
|---|--|----------------------|----------|----------|----------|----------|----------|----------|----------|
| | | <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> | <u>5</u> | <u>6</u> | <u>7</u> | <u>8</u> |
| A X I S O R I E N T A T I O N | | 0 | 0 | 0 | 0 | 0 | 0 | +1g | +1g |
| | | -1g | -1g | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 0 | 0 | 0 | 0 | 0 | 0 | -1g | -1g |
| | | +1g | +1g | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 0 | 0 | -1g | -1g | -1g | -1g | 0 | 0 |
| | | 0 | 0 | +1g | +1g | +1g | +1g | 0 | 0 |

Figure 3-23. Accelerometer Calibration Matrix

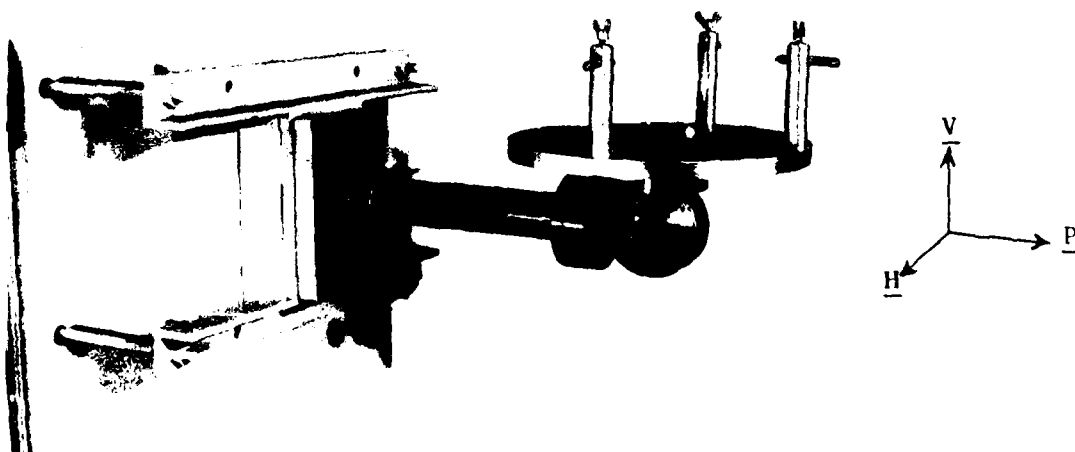


Figure 3-24. Accelerometer Calibration Rig.

For example if the null g position is used then

$$B = -S_F V_{\text{null}} \quad (3.32)$$

To calibrate the eight accelerometers the platform was placed in six positions with respect to the vertical plane. The coordinate system orientation and the resulting g readings for each accelerometer are shown in Figure 3-23. By recording the voltage readings for each of the six positions, the required scale factors and offsets were then computed from equations (3.30) and (3.31).

A calibration rig was constructed to hold the accelerometer platform and rotate it through the six calibration positions. As shown in Figure 3-24, the calibration rig was rigidly mounted to a steel supporting column. Three indexing heads were incorporated in the design to allow the mounting platform to be rotated through 360° about any of three axis. Setting pins in each indexing head provided positive position stops at the 0° , 90° , 180° and 270° positions on each axis.

In order to ensure that the accelerometers were rotated in a true vertical plane, the calibration rig had to be carefully aligned. To facilitate the alignment three grub screw were located in the column mounting collar which allowed the mounting column to be secured after rotation about its horizontal axis. A dual backing plate with three positioning grub screws and three locking bolts for vertical and lateral positioning was incorporated in the design. The alignment screws are shown in Figure 3-25.

Initial alignment of the calibration rig was made with the mounting platform horizontal as shown in Figure 3-24. The leveling instrument used was an eight inch Moore and Wright Engineers Level on which one bubble division is equivalent to 0.0167° . The level was placed on top of the mounting platform and parallel to the H axis. First the V axis was aligned

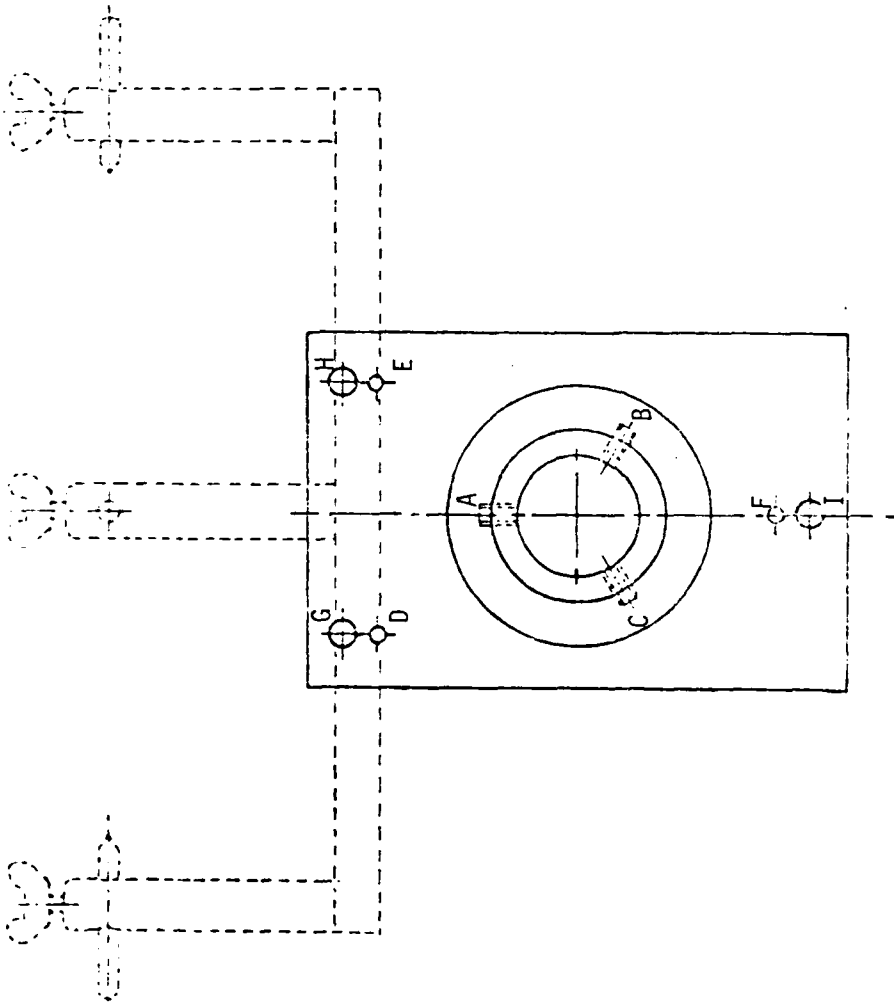


Figure 3-25. Calibration Rig Adjustment Screws.



Figure 3-26. Calibration Rig Tent and Thermal Control System.

with the vertical by loosening grub screws A, B, and C; rotating the mounting column until the bubble indicated that the platform was level; then retightening the grub screws. The mounting column was adjusted as necessary until the bubble remained level when the platform was rotated through 180° (to align the bubble in both the $+\underline{H}$ and $-\underline{H}$ direction) using the indexing head. Next the indexing head was used to rotate the platform 90° to position the bubble level parallel to the \underline{P} axis. The backing plate locking screws G, H and I were loosened and grub screws D, E and F were used to adjust the bubble to a level position. After securing the locking screws, the platform was rotated through 180° (to align the bubble level in both the $+\underline{P}$ and $-\underline{P}$ directions). The grub and locking screws were adjusted as necessary to maintain the bubble in a level position along both the $+\underline{P}$ and $-\underline{P}$ directions. These procedures were repeated as necessary until the bubble was maintained in the same position while the mounting platform was rotated through 360° using the indexing head. This procedure ensured that the mounting platform was rotating about a vertical axis.

After the alignment procedure was completed, the maximum deviation of the bubble from a level position was ± 4 divisions. This corresponds to an error of $\pm 0.067^\circ$ during 360° of rotation or 0.02 %. The platform was then rotated into the vertical plane and indexed through the 90° , 180° and 270° positions. The angles were measured with the leveling protractor from a machinists combination set and the maximum measured error for the fixed positions was 0.5° . Therefore, the maximum error in the calibration rig was less than $\pm 0.45^\circ$ in 360° and the angular position of the calibration rig was accurate to ± 0.3 %.

As discussed earlier in this chapter, zero shift due to thermal drift can be a major problem if the temperature of the accelerometers are not maintained at a constant value during calibration and data acquisition. To prevent this problem and maintain a stable temperature environment, the

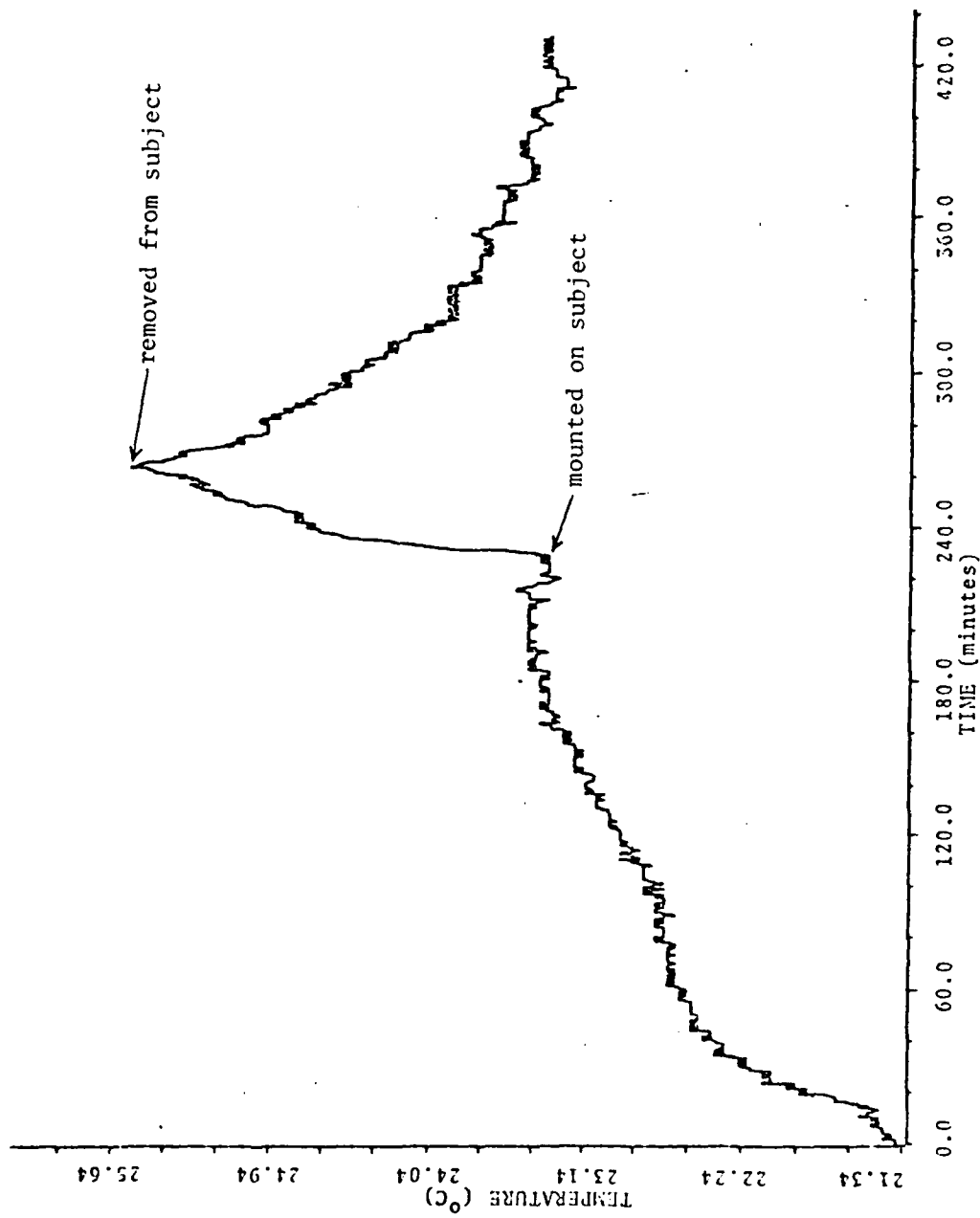


Figure 3-27. Typical Temperature Test.

calibration rig was enclosed in a plastic tent which was open at the bottom. A thermistor driven temperature control circuit was connected to a standard fan heater positioned beneath the tent as shown in Figure 3-26. Using this system the temperature of the calibration rig and accelerometers could be maintained at any desired value from room temperature to $40^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$.

By placing a thermistor inside the accelerometer package and recording the output on a miniature tape recorder, it was possible to monitor the internal temperature of the body mount under different conditions. A typical test is shown in Figure 3-27 in which the system was turned on and allowed to warm to a stable temperature, then attached to a subject for 30 minutes and then allowed to return to room temperature. This and similar tests indicated that:

- (1) from a "cold" start (about 20°C) a minimum of 2 hours 45 minutes is required to reach a stable operating temperature,
- (2) when stabilized to room temperature the accelerometer temperature will change at a rate of $0.1^{\circ}\text{C}/\text{minute}$ if the body mount is attached to a subject,
- (3) when removed from the subject the accelerometer temperature requires another 2 hours 45 minutes to return to room temperature.

Additional tests were performed and it was found that if the accelerometer body mount was stabilized at a temperature approximately midway between body temperature (37°C) and room temperature, the internal body mount temperature would change less than 1°C during a 30 minute period. Also the internal body mount temperature would return to the stabilized temperature within 10 minutes after being removed from the subject. A typical series of these tests is shown in Figure 3-28 where the

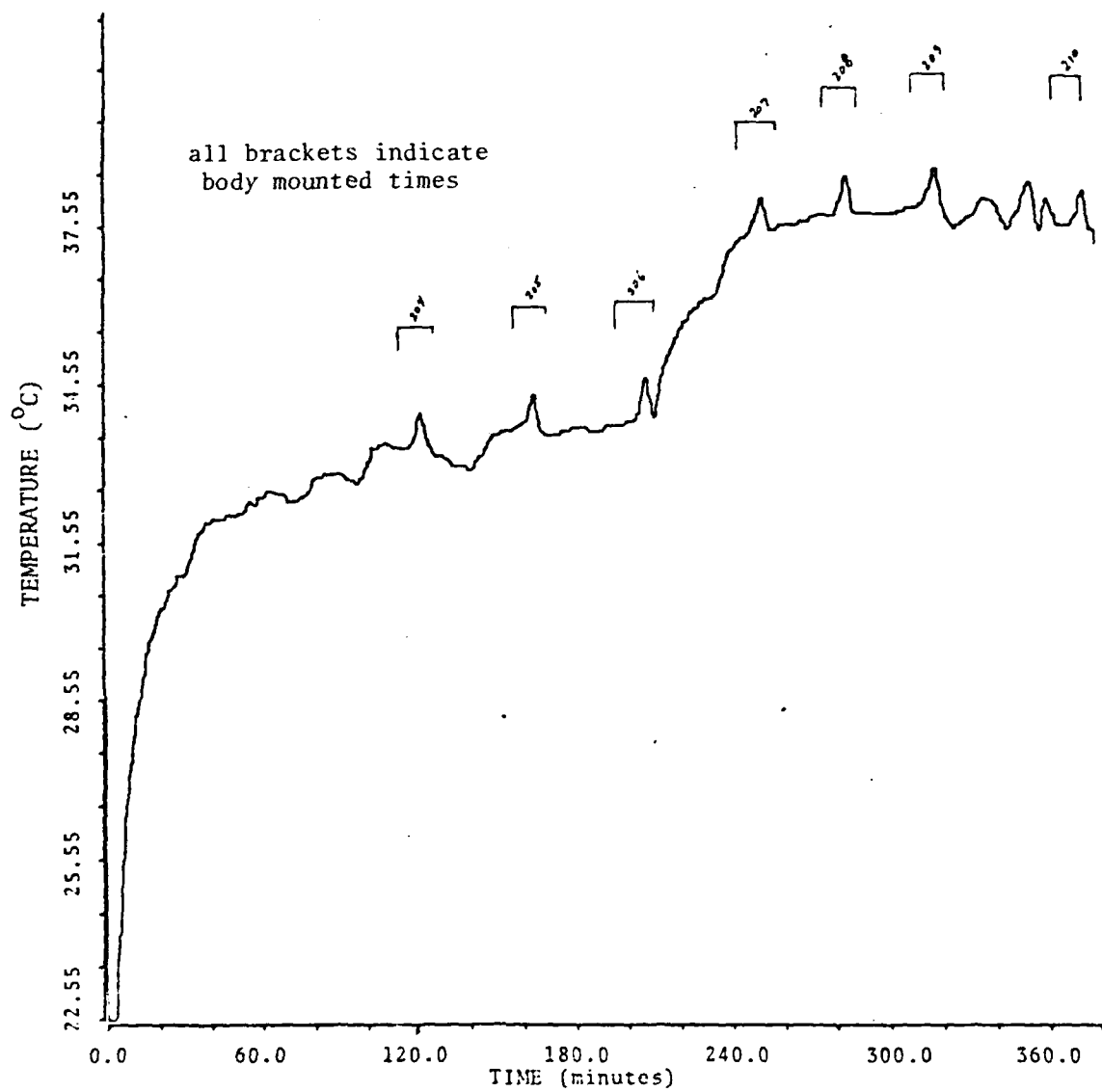


Figure 3-28. Typical Series of Temperature Tests.

bracketed data sections indicate when the body mount was attached to the subject and data collected.

Having described the design, fabrication, testing and operation of the experimental apparatus, the experimental method used to acquire and process data from subjects will be presented in the next chapter.

CHAPTER 4

THE EXPERIMENTAL METHOD

- 4.1 Introduction
- 4.2 Equipment Preparation and Calibration
- 4.3 Walking Test Sequences and Data Collection
- 4.4 Data Processing
- 4.5 Mathematical Methods used in Data Processing
- 4.6 Testing of the Experimental Method

4.1 Introduction

The experimental method used to collect and process data is presented in this chapter. A description of the method for preparing and calibrating the accelerometer equipment is followed by a discussion of the walking test sequences and the procedure for collecting and storing data on the computer during walking tests. The data processing sequence and a brief description of the computer programs used in this sequence is presented. The complete listings for these computer programs are contained in Appendix F. The mathematical methods used to integrate and filter the data along with a discussion of the initial conditions required to begin the integration are presented in a separate section following the data processing section. The chapter concludes with a description and discussion of the experimental tests conducted to determine the effectiveness of the accelerometer method developed in this study.



Figure 4-1. Accelerometer Body Mount Installed on Calibration Rig.

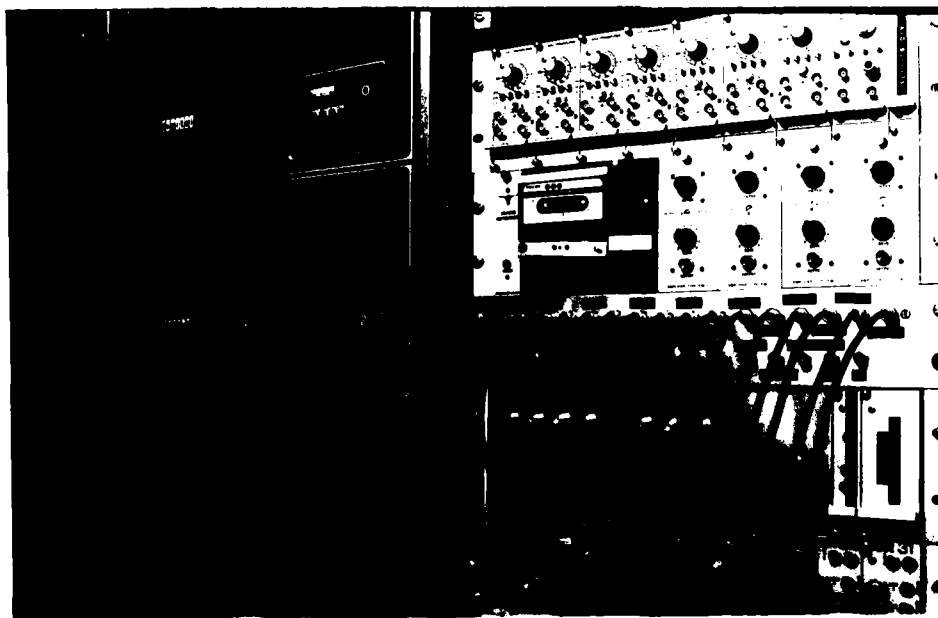


Figure 4-2. Electronic Equipment Rack Cabling.

4.2 Equipment Preparation and Calibration

The preparation and calibration of the measurement system equipment for subject testing consisted of installing the body mount on the calibration rig, temperature stabilizing the body mount and calibrating the accelerometers. The initial temperature stabilization period, from a cold start (20°C), was approximately 2 3/4 hours. When this initial temperature stabilization had been completed, the remaining equipment preparation and calibration was completed in 10 minutes. The following paragraphs describe the procedure to be performed for a cold start.

The body mount was installed on the calibration rig using three adjustable pins with wing screws. The pins had tapered ends which fit into locator holes in the ends of the aluminum accelerometer platform. The wing screws were used to secure the pins and were alternately loosened and tightened to properly secure the body mount to the calibration rig. The body mount, installed on the calibration rig, is shown in Figure 4-1.

After installing the body mount on the calibration rig, the subminiature 15 way cable was connected to the electronic equipment rack. At this time the 16 coaxial cables which carried the output signals from the amplifiers to the ADC were connected. The electronic equipment rack, with the cables installed, is shown in Figure 4-2. The power was then applied to the electronic equipment. Power to the accelerometers in the body mount was supplied through the subminiature 15 way connecting cable.

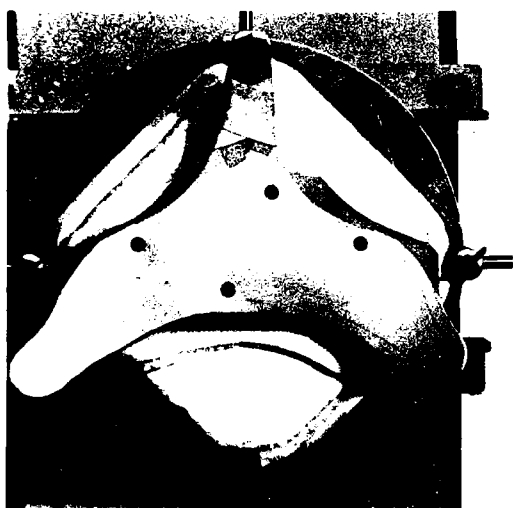
As discussed in chapter 3 (pp. 84-86), the body mount, containing the accelerometers, had to be maintained at a relatively constant temperature to ensure that the zero offset voltage remained constant during calibration and data collection. The thermal zero shift of the accelerometers was less than 0.005 g's/°C, from Figure 3-10. For a peak to peak signal of 1 g, the zero shift would be 1% for each 2 °C change in the temperature of the accelerometers. The temperature stabilization procedure



Position 1



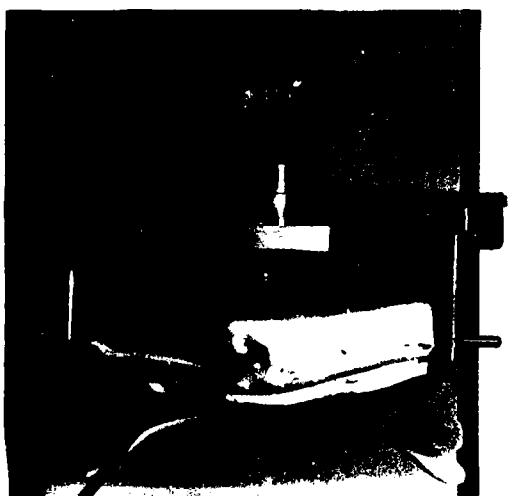
Position 2



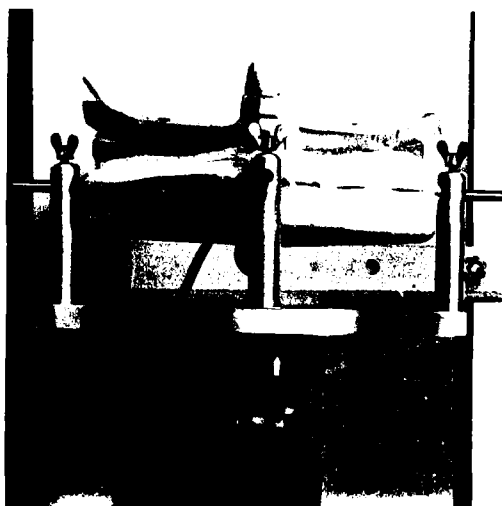
Position 3



Position 4



Position 5



Position 6

Figure 4-5. The Six Calibration Positions.

was developed to ensure that the temperature of the accelerometers did not change more than $\pm 1^{\circ}\text{C}$ during calibration and data collection.

The temperature stabilization procedure began when the power to the electronic equipment was turned on. The plastic tent was placed over the calibration rig and the fan heater and temperature control unit positioned beneath the tent. The thermostatic control was then adjusted to the desired temperature, normally $28-30^{\circ}\text{C}$, and the fan heater turned on. Approximately $2\frac{3}{4}$ hours was required for temperature stabilization. The temperature was monitored during this period with a thermometer located in the plastic tent. After the temperature had been stabilized, the calibration procedure was performed.

Calibration of the accelerometers was accomplished by running computer program CALIB1 and rotating the calibration rig through the 6 positions which were described in chapter 3(pp. 82-83). With the calibration rig in position 1, as shown in Figure 4-3, the operator started program CALIB1 and entered the data record number, subject number and a code which indicated if the calibration was being performed before or after the walking data had been collected. The computer then displayed on the terminal screen

"CR TO TAKE DATA SAMPLE"

which indicated that the accelerometer output voltages for position 1 would be sampled and stored when the operator depressed the <carriage return>(<CR>) key. The calibration rig was then indexed through the remaining 5 positions, also shown in Figure 4-3, and the accelerometer output voltages were sampled and stored for each position by depressing the <CR> key when the above message was displayed. The calibration rig was held in each position for one minute to ensure that the accelerometer output voltages had stabilized before the data sample was stored.

BEFORE AND AFTER CALIBRATION FOR SUBJECT NUMBER: 1
CALIBRATION DATA TABLE (IN VOLTS) DATE: 23-MAY-78 TIME: 18:02:21

| CHANNEL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|--------|--------|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|--------|
| 1 | -0.001 | 0.000 | 0.001 | 0.002 | 0.000 | 0.000 | 1.679 | 1.677 | 0.000 | -0.003 | 0.004 | 0.002 | 0.005 | 0.000 | 0.000 | 1.000 |
| 2 | -0.004 | -0.004 | -0.000 | -0.010 | 0.012 | 0.002 | 0.688 | 0.813 | 0.020 | -0.039 | 0.046 | -0.376 | 0.993 | 0.019 | -0.005 | 0.072 |
| 3 | 0.011 | -0.013 | -0.039 | 0.002 | 0.023 | 0.001 | -0.319 | 0.322 | 0.081 | -0.197 | 0.109 | 0.000 | 0.001 | 0.020 | -0.010 | -1.006 |
| 4 | 1.007 | 1.002 | -0.020 | 0.017 | 0.010 | 0.001 | 0.657 | 0.697 | 0.018 | -0.166 | 0.065 | -0.117 | -1.002 | 0.005 | -0.001 | -0.001 |
| 5 | 0.008 | 0.016 | 0.065 | 0.990 | 1.001 | 0.996 | 0.658 | 0.684 | -0.020 | -0.108 | 0.038 | -0.078 | -0.009 | -0.971 | -0.996 | -0.004 |
| 6 | 0.023 | -0.005 | -1.005 | -0.997 | -0.992 | -1.002 | 0.671 | 0.607 | 0.093 | -0.144 | 0.051 | -0.055 | -0.007 | 1.011 | 1.001 | 0.000 |

MEAN SCALE FACTORS AND OFFSETS FOR RECORD: 1
SUBJECT: 1
DATE: 23-MAY-78

| CHANNEL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|--------|--------|--------|--------|--------|
| 1 | -0.0006 | -0.001 | 0.003 | 0.003 | 0.000 | 0.000 | 1.680 | 1.680 | -0.010 | 0.000 | 0.010 | 0.002 | 0.004 | 0.000 | 0.000 | 1.000 |
| 2 | -0.000 | -0.002 | -0.010 | -0.010 | 0.014 | 0.001 | 0.689 | 0.815 | 0.005 | -0.034 | 0.051 | -0.378 | 0.993 | 0.020 | -0.005 | 0.072 |
| 3 | 0.005 | -0.015 | -0.045 | 0.000 | 0.023 | 0.000 | -0.320 | -0.320 | 0.038 | -0.190 | 0.114 | 0.000 | 0.006 | 0.020 | -0.013 | -1.006 |
| 4 | 1.004 | 1.004 | -0.017 | 0.017 | 0.014 | 0.000 | 0.660 | 0.702 | 0.007 | -0.163 | 0.067 | -0.119 | -1.001 | 0.001 | 0.000 | 0.000 |
| 5 | 0.006 | 0.015 | 0.063 | 0.987 | 1.002 | 0.995 | 0.659 | 0.684 | -0.030 | -0.107 | 0.040 | -0.033 | -0.008 | -0.972 | -0.992 | -0.001 |
| 6 | 0.021 | -0.008 | -1.003 | -0.997 | -0.993 | -1.005 | 0.672 | 0.607 | 0.084 | -0.139 | 0.057 | -0.058 | -0.005 | 1.012 | 1.002 | 0.000 |

AFTER AND AFTER CALIBRATION FOR SUBJECT NUMBER: 1
CALIBRATION DATA TABLE (IN VOLTS) DATE: 23-MAY-78 TIME: 18:27:58

| CHANNEL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|--------|--------|--------|--------|--------|
| 1 | -0.006 | -0.001 | 0.003 | 0.003 | 0.000 | 0.000 | 1.680 | 1.680 | -0.010 | 0.000 | 0.010 | 0.002 | 0.004 | 0.000 | 0.000 | 1.000 |
| 2 | -0.000 | -0.002 | -0.010 | -0.010 | 0.014 | 0.001 | 0.689 | 0.815 | 0.005 | -0.034 | 0.051 | -0.378 | 0.993 | 0.020 | -0.005 | 0.072 |
| 3 | 0.005 | -0.015 | -0.045 | 0.000 | 0.023 | 0.000 | -0.320 | -0.320 | 0.038 | -0.190 | 0.114 | 0.000 | 0.006 | 0.020 | -0.013 | -1.006 |
| 4 | 1.004 | 1.004 | -0.017 | 0.017 | 0.014 | 0.000 | 0.660 | 0.702 | 0.007 | -0.163 | 0.067 | -0.119 | -1.001 | 0.001 | 0.000 | 0.000 |
| 5 | 0.006 | 0.015 | 0.063 | 0.987 | 1.002 | 0.995 | 0.659 | 0.684 | -0.030 | -0.107 | 0.040 | -0.033 | -0.008 | -0.972 | -0.992 | -0.001 |
| 6 | 0.021 | -0.008 | -1.003 | -0.997 | -0.993 | -1.005 | 0.672 | 0.607 | 0.084 | -0.139 | 0.057 | -0.058 | -0.005 | 1.012 | 1.002 | 0.000 |

MEAN SCALE FACTORS AND OFFSETS FOR RECORD: 1
SUBJECT: 1
DATE: 23-MAY-78

| CHANNEL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|--------|--------|--------|--------|--------|
| 1 | -0.0006 | -0.001 | 0.003 | 0.003 | 0.000 | 0.000 | 1.680 | 1.680 | -0.010 | 0.000 | 0.010 | 0.002 | 0.004 | 0.000 | 0.000 | 1.000 |
| 2 | -0.000 | -0.002 | -0.010 | -0.010 | 0.014 | 0.001 | 0.689 | 0.815 | 0.005 | -0.034 | 0.051 | -0.378 | 0.993 | 0.020 | -0.005 | 0.072 |
| 3 | 0.005 | -0.015 | -0.045 | 0.000 | 0.023 | 0.000 | -0.320 | -0.320 | 0.038 | -0.190 | 0.114 | 0.000 | 0.006 | 0.020 | -0.013 | -1.006 |
| 4 | 1.004 | 1.004 | -0.017 | 0.017 | 0.014 | 0.000 | 0.660 | 0.702 | 0.007 | -0.163 | 0.067 | -0.119 | -1.001 | 0.001 | 0.000 | 0.000 |
| 5 | 0.006 | 0.015 | 0.063 | 0.987 | 1.002 | 0.995 | 0.659 | 0.684 | -0.030 | -0.107 | 0.040 | -0.033 | -0.008 | -0.972 | -0.992 | -0.001 |
| 6 | 0.021 | -0.008 | -1.003 | -0.997 | -0.993 | -1.005 | 0.672 | 0.607 | 0.084 | -0.139 | 0.057 | -0.058 | -0.005 | 1.012 | 1.002 | 0.000 |

Figure 4-4. Sample Calibration Program(CALIB1) Output.

After the voltages for position 6 had been sampled and stored, program CALIB1 computed, using equations (3.30) and (3.31), the scale factors and zero offset voltages for each of the eight accelerometers and the four summing and four difference amplifiers. The raw voltage samples, and the computed scale factors and offsets, were then stored for future use in data file CALIBD.DAT, and printed out on the line printer for examination. A sample output is shown in Figure 4-4 where the sampled output voltages for each of the 16 channels (accelerometers: channels 1-8, difference amplifiers: channels 9-12, summing amplifiers: channels 13-16) for positions 1-6 appear in the calibration data table. The computed scale factors and zero offset voltages were then printed for each of the 16 channels.

During walking tests, calibration was performed before and after walking data collection and the mean scale factors and offsets used to convert walking voltages to acceleration (in g's). Therefore, the printed output showed the before and after walk calibration and the mean scale factors and offsets computed when both calibrations had been completed. During the before walk calibration, it was desirable to set the offsets to near zero volts and the scale factors equal for each accelerometer pair. This was not essential, but if the calibration output values were not in the acceptable range, then the gains and offsets of each accelerometer could be adjusted with the potentiometers provided on the electronic equipment. The calibration procedure was then repeated until acceptable values were obtained.

After successful completion of the calibration procedure, the subject walking tests and data collection were started. These are discussed in the following section.

MALE SUBJECTS:

| <u>Subject Number</u> | <u>Age</u> | <u>Height (cm)</u> | <u>Weight (kg)</u> |
|-----------------------|------------|--------------------|--------------------|
| 1 | 40 | 186.5 | 93.0 |
| 2 | 25 | 177.0 | 63.5 |
| 3 | 44 | 170.5 | 77.5 |
| 4 | 32 | 186.0 | 86.5 |
| 5 | 28 | 177.0 | 69.5 |
| 6 | 35 | 175.0 | 74.0 |
| 7 | 23 | 173.5 | 71.4 |

FEMALE SUBJECTS:

| <u>Subject Number</u> | <u>Age</u> | <u>Height (cm)</u> | <u>Weight (kg)</u> | <u>HEEL HEIGHT</u> | |
|-----------------------|------------|--------------------|--------------------|--------------------|-----------------|
| | | | | <u>Low(cm)</u> | <u>High(cm)</u> |
| 8 | 23 | 160.5 | 54.2 | 3.6 | 7.1 |
| 9 | 29 | 157.0 | 49.2 | 4.6 | 8.4 |
| 10 | 26 | 154.8 | 52.6 | 3.8 | 8.5 |
| 11 | 27 | 153.0 | 64.5 | 2.0 | 7.8 |
| 12 | 24 | 161.0 | 60.9 | 3.3 | 6.8 |
| 13 | 27 | 162.5 | 54.0 | 2.1 | 5.8 |
| 14 | 31 | 161.5 | 56.0 | 2.9 | 6.5 |

Mean Heel Rise = 4.1 cm

Table 4-1. Subject Data.

4.3 Walking Test Sequences and Data Collection

The same basic walking and data collection method was used for all walking tests. The walking tests were conducted in the OOEC gait laboratory and consisted of straight and level walking for a distance of 9 to 10 meters. The subjects were free to choose their own cadence for the walking tests.

The testing began with a subject interview at which time the subjects were weighed and measured; the results are shown in Table 4-1. The heel heights of the low and high heeled shoes of the female subjects were also measured. The subjects wore their own shoes during the tests and were allowed to select the heel heights, but were asked to bring shoes which they considered to have low and high heels. After the measurements were completed, the test sequences were explained to the subject. Normally, the accelerometers were being calibrated simultaneously with the subject interview. This allowed the walking test sequences to be started immediately following the interview.

After the interview, the subjects changed into test clothing. For male subjects, walking shorts with a loose elastic waist band were provided while a modified, knee length hospital gown was provided for female subjects. All subjects were allowed to wear their own undergarments. After dressing, the temperature stabilized and calibrated body mount was fitted to the sacrum of the subject. The subjects then walked about the gait laboratory for five minutes to become accustomed to the body mount and any adjustments necessary to tighten or reposition the body mount were made.

The walking test sequence began with the subject standing in a stationary position at one end of the walkway. After the operator started the computer data collection program, DATLRG, the subject remained in the stationary position for approximately three seconds. Then, at a signal

given by the operator, the subject walked to the end of the walkway(10 meters), stopped and again remained stationary until the operator indicated that data collection was complete(approximately 3-5 seconds after stopping). Therefore, each basic walking test sequence consisted of 3 seconds of standing, 9-10 seconds of walking, and 3 seconds of standing. The computer program, DATLRG, displayed the data collected on the terminal screen while it was being stored in the computer memory, and a decision on the suitability of the test data for further analysis was made at the time of the test. If the data did not appear suitable, the test was repeated immediately. A further description of DATLRG will be presented at the end of this section.

The same basic test sequence, which required approximately 20 seconds to complete, was repeated for the three walking tests of female subjects. The first walking test consisted of the subject performing the basic test in bare feet. During the second test the female subjects wore low heeled shoes. For the third, and final test, the female subjects walked in high heeled shoes. Each complete testing sequence, for female subjects, consisted of a calibration, three walks(bare feet, low heeled shoes, high heeled shoes), and a second calibration. The entire procedure was completed in less than 30 minutes.

The three walking tests performed on male subjects were also completed within 30 minutes. For the first two tests, the male subjects also walked in bare feet and in low heeled shoes. For the third walk, the male subjects were fitted with a backpack containing 13.6 Kg(30 pounds weight) of sand. In this third test the male subjects wore the same low heeled shoes as in the second walking test. Data collection was again accomplished using computer program DATLRG.

The data collection program, DATLRG, was a slightly modified, general purpose data collection program originally used by Morris(1973). It was modified to allow data collection and storage in the PDP 11/34 at the OOEK. The program was interactive, with the operator initially entering the number of channels to be sampled, the sampling time, and the total run time for the test being performed. For the walking tests, 16 channels were sampled every 5 milliseconds(200 Hz) for a total of 15.99 seconds. When the subjects indicated they were ready to begin the basic walking sequence, data collection and storage was initiated by the operator depressing the <CR> key. The data being stored was displayed on the terminal screen for preliminary analysis. This allowed the operator to determine if any gross discrepancies occurred during data collection and, if necessary, rerun the test immediately. The data was stored by a record number, selected by the operator, in data file ADC.DAT, and could be recalled, using the record number, at any time for further data processing.

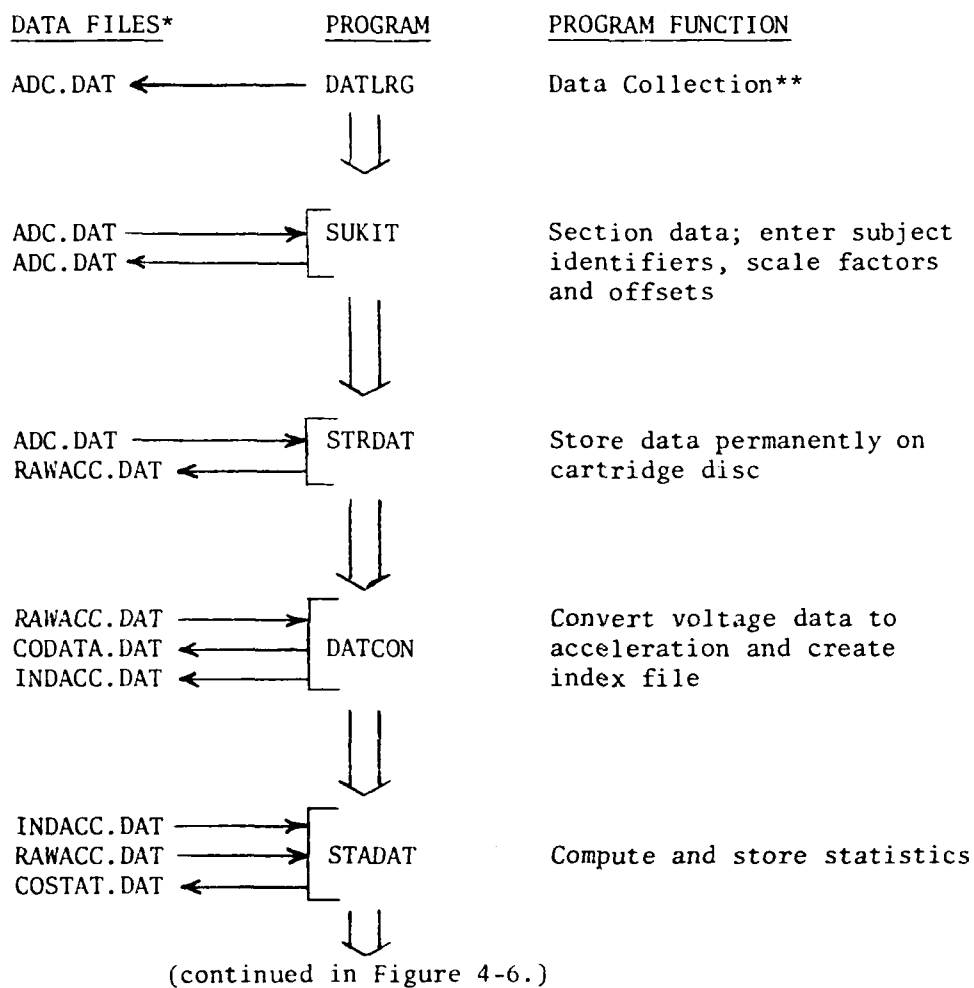
The processing of data collected and stored during the walking tests will be discussed in the following section.

4.4 Data Processing

The purpose of the data processing programs was to produce graphic records of the rotational and translational parameters calculated from the data collected during the walking tests. The programs implemented the theoretical equations explained in chapter 2 and the programs followed the sequence of the theory presented in that chapter. Additional mathematical methods were required in this implementation and these are discussed in the following section. A brief description of each of the programs used to process walking test data is presented in this chapter. Complete listings of all the computer programs are contained in Appendix F and may be consulted as necessary.

The programs were written in FORTRAN for processing on the PDP 11/34 computer located in the OOEK gait laboratory. This computer used the DEC RT-11 operating system and an RK05 cartridge disc for storing data files and programs. Some additional processing and analysis was performed using the PDP 11/45 computer in the F. J. Seiler Research Laboratory, U.S. Air Force Academy, Colorado. This computer uses the RSX-11 operating system and therefore some minor modifications to the programs were required. These modifications were necessary to accommodate the slightly different methods used by the operating systems to input and output data files. The basic FORTRAN coding and program structure remained unchanged.

The sequence of programs required to process the data is shown, in order, in Figures 4-5 through 4-9. The sequence was broken for the convenience of the reader so that he could refer to the sequence, while reading the program description, without finding it necessary to change pages. The programs appear in the sequence in which they were run. The input and output data files as well as the function of the program are presented in the corresponding figure.



* → Input data file
 ← Output data file

**Program run during subject walking tests.

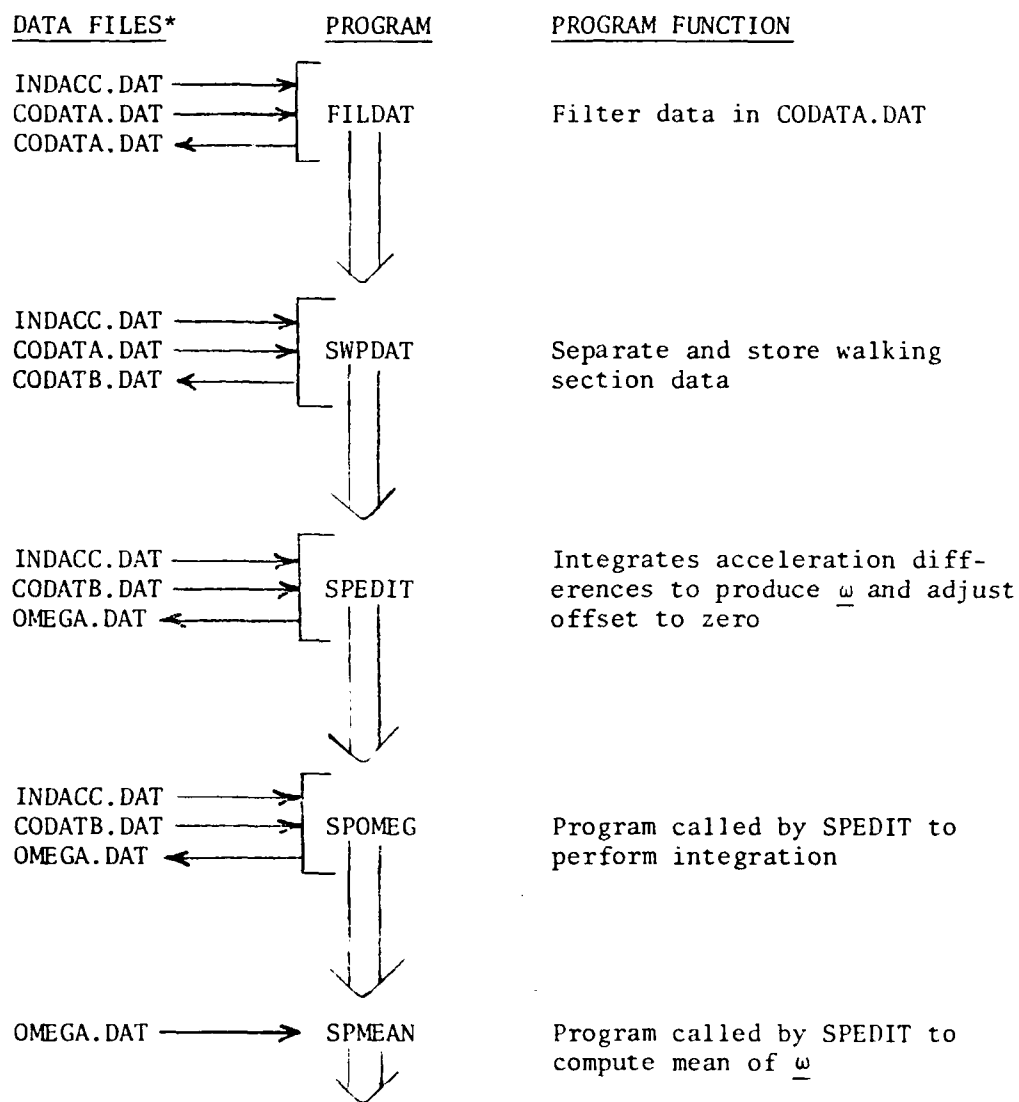
Figure 4-5. Data Processing Program Sequence

After data had been collected and stored in ADC.DAT, program SUKIT was run. This program was an interactive, general purpose program used to section data, to enter subject and test identifiers and the scale factors and offsets computed by the calibration procedure. After the identifiers and other parameters were entered, the data was displayed for sectioning. In this study, the data was divided into three sections; the initial standing phase, the walking phase, and the final standing phase. After sectioning, the data which had been entered and the indexes for the locations of the sectioned data were stored in ADC.DAT.

The sectioned data was then permanently stored on a magnetic cartridge disc with program STRDAT. The data, with its associated identifiers, scale factors and offsets, was transferred from input file ADC.DAT to the output file RAWACC.DAT. The output data file was located on a cartridge disc installed in the RK05. Each cartridge disc was capable of storing the data for the three walking tests performed by seven different subjects. The cartridge discs provided a method for permanently storing data collected during subject tests.

The processing of the permanently stored data was begun by running program DATCON. The purpose of this program was to convert the data from output voltages to accelerations(in g's) using the scale factors and zero offset voltages from the calibration procedure. The program also produced an indexing file, INDACC.DAT, which was used by all the following programs to access the correct data locations. The program read data from RAWACC.DAT and implemented equation (3.29) to convert the data from voltage to acceleration(in g's). The converted data was stored in output file CODATA.DAT for use in the following programs.

Program STADAT was used to compute statistics on each of the standing and the walking sections of the data. The mean, maximum, minimum, variance and standard deviation was computed for each of the 16 channels. The pair



(continued in Figure 4-7.)

* → Input data file
 ← Output data file

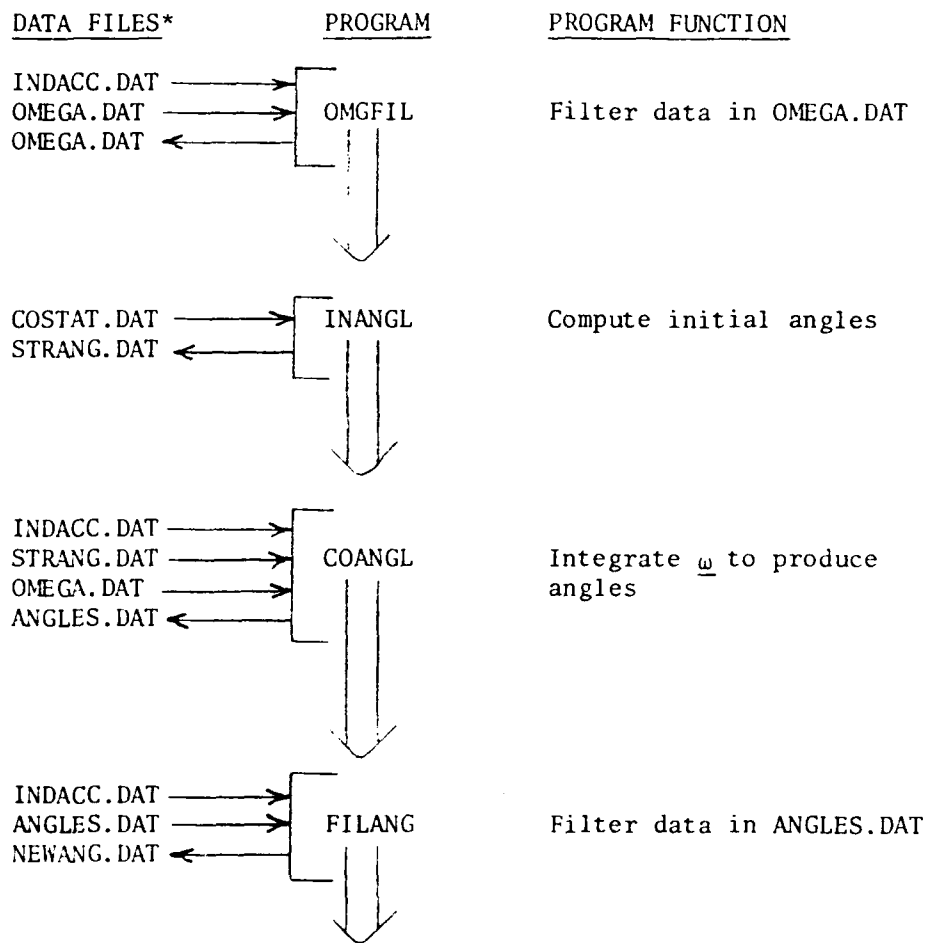
Figure 4-6. Data Processing Program Sequence(continued)

mean value for each accelerometer pair was computed for use in program INANGL where the initial, standing position, angles were determined. The statistics were stored in data file COSTAT.DAT and printed out on the line printer.

The converted data, stored in CODATA.DAT, was then filtered to remove undesirable high and very low frequency noise using program FILDAT. The filtering method is described in section 4.5 and is an eighth order, recursive Butterworth bandpass filter. The filtering subroutine BNDPAS was used by all the filtering programs. Program FILDAT read data from CODATA.DAT, filtered it by calling subroutine BNDPAS, and then stored the filtered acceleration data in CODATA.DAT. The original unfiltered data in CODATA.DAT was replaced by the filtered data.

All three data sections were stored in CODATA.DAT. Program SWPDAT was used to remove the walking section data, section 2, and store it in a new data file. Program SWPDAT read data from CODATA.DAT and, using the indexing information from INDACC.DAT, separated the walking section data and stored it in output data file CODATB.DAT for use in the following programs.

The next program in the sequence, SPEDIT, was an iterative program which called the following two programs, SPOMEG and SPMEAN, to produce the angular velocity vector, $\underline{\omega}$. The accelerometer pair differences were input from CODATB.DAT for integration by program SPOMEG which was automatically called by SPEDIT. This program, and all other integration programs, used subroutine AM3INM and a subroutine containing the differential equations to be integrated, in this case subroutine DIOMGH, to perform the required integration. The integration method, an Adams-Moulton predictor corrector, will be discussed in section 4.5. The program SPOMEG, and its equation subroutine, implemented the integration of equations (2.31), (2.32) and (2.32) and produced the angular velocity vector, $\underline{\omega}$. After the integration



(continued in Figure 4-8.)

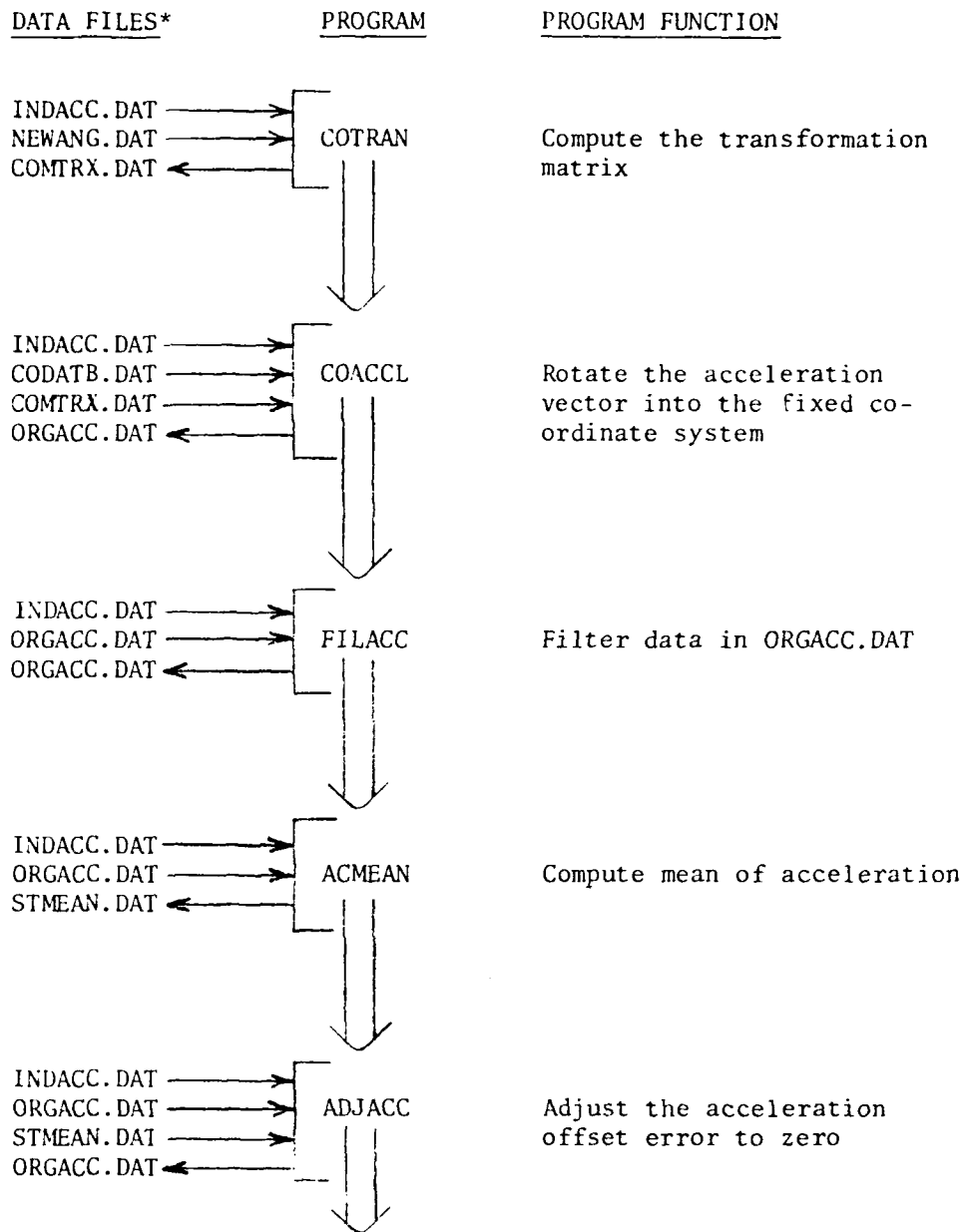
* → Input data file
 ← Output data file

Figure 4-7. Data Processing Program Sequence(continued)

was completed, SPEDIT called program SPMEAN to compute the mean value of each of the three components of $\underline{\omega}$. The means were then used to compute an offset correction factor which was subtracted from the input data during the next integration. The rationale for this correction will also be presented in section 4.5. The integration was then repeated and the means were recomputed. This iterative procedure was continued until the mean values of all three components of $\underline{\omega}$ were less than a specified tolerance, in this study 1×10^{-5} . Thus, SPEDIT produced, by integrating accelerometer pair differences, an angular velocity vector, $\underline{\omega}$, with zero mean value and stored this vector in data file OMEGA.DAT. To remove any low frequency oscillations which may have been produced by the integration process, the data in OMEGA.DAT was then filtered by program FILONG which used the same filtering subroutine, BNDPAS, previously described. The unfiltered data originally stored in OMEGA.DAT was replaced by the filtered data.

Following computation of the angular velocity, the initial values of the angles which describe the orientation of the pelvis during standing were computed. The program INANGL calculated these angles from the mean values of the accelerometer readings measured during the initial standing phase of the walking tests. These mean values were computed, and stored in COSTAT.DAT, by program STADAT. Using COSTAT as the input data file, INANGL computed the initial angles and stored them in data file STRANG.DAT for use in program COANGL. The method used to compute these initial angles will be presented in detail in section 4.5.

With the initial angles computed, program COANGL was run to integrate equations (2.60), (2.61) and (2.62) and produced the angles ϕ , θ , and ψ . These three angles defined the orientation of the pelvis during the walking phase. This program also used subroutine AM31NM as the integration routine and the differential equations were contained in subroutine



(continued in Figure 4-9.)

* → Input data file
 ← Output data file

Figure 4-8. Data Processing Program Sequence(continued)

DIANGL. After computation, the angles were filtered by program FILANG and stored in data file NEWANG.DAT.

With the angles determined, the transformation matrix could be computed. The transformation matrix was computed by running program COTRAN which implemented equation (2.46), the equation which defined the transformation matrix in terms of angles ϕ , θ , and β . The program read the angles from NEWANG.DAT, performed the required trigonometric computations and stored the resulting transformation matrix in COMTRX.DAT. It was now possible to transform any vector measured in the body-centered coordinate system into the fixed coordinate system and vice versa.

The program COACCL implemented the theory regarding the computation of the acceleration of the pelvis discussed in section 2.5. The sum of the accelerations measured by one pair of accelerometers was transformed into the fixed coordinate system by implementing equation (2.71). The acceleration of the pelvis was then computed by subtracting the gravitational acceleration from the transformed measured acceleration, equation (2.73). The resulting acceleration, the acceleration of the pelvis in the fixed coordinate system, was then stored in ORGACC.DAT.

The acceleration data in ORGACC.DAT could contain small offset errors which were removed by running the next three programs in the sequence. Program FILACC, the filtering program, removed the unwanted low and high frequency signals from the data. The mean value of the acceleration was then computed by program ACMEAN and the computed means were stored in data file STMEAN.DAT. The mean of the acceleration was then adjusted to zero by program ADJACC which read the accelerations from ORGACC.DAT, subtracted the mean values stored in STMEAN.DAT and then stored the acceleration values, with zero mean, in data file ORGACC.DAT. The rationale for this sequence of processing will also be presented in section 4.5.

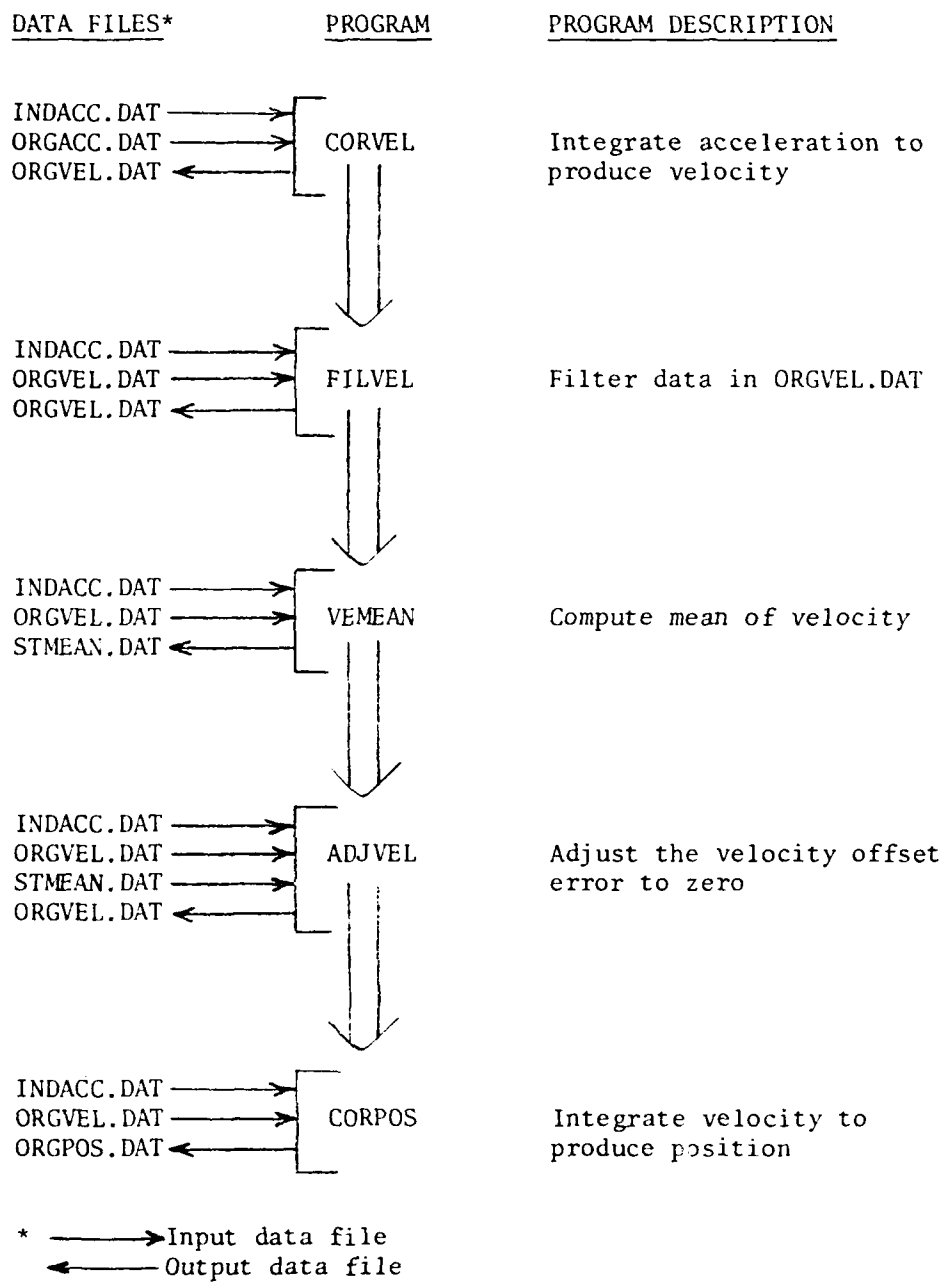


Figure 4-9. Data Processing Program Sequence(continued).

Using a similar method, the velocity was computed by programs CORVEL, FILVEL, VEMEAN and ADJVEL. The accelerations stored in ORGACC.DAT were input to program CORVEL which performed the necessary integration and stored the integrated velocity in data file ORGVEL.DAT. The data was then filtered, with program FILVEL, and the mean values computed, with program VEMEAN. The mean value of the velocity was adjusted to zero by running program ADJVEL and the results were stored in ORGVEL.DAT.

The final step in the data processing sequence was the integration of the velocity to obtain position. This integration was performed by program CORPOS which read the velocity data stored in ORGVEL.DAT, integrated it and stored the output in ORGPOS.DAT. The data files now contained all the rotational and translational parameters which described the three dimensional motion of the pelvis during the walking phase of the subject tests.

The preceding programs could either be run separately, in an interactive mode, or automatically using the command file program, DATRUN. This program sequentially initiated and ran the data processing programs beginning with DATCON and finishing with CORPOS. When run on the PDP 11/45 computer, the data could be processed and all data files stored in eight minutes. The stored data files could then be analyzed.

To facilitate the viewing and analyzing of the rotational and translational parameters, a program to plot the data on the terminal screen, PLOTIT, was developed. This program displayed the computed data, in graphical form, on a Tektronics storage terminal screen. The program was interactive and allowed the operator to plot either all the data in a particular data file, or selected portions of the data file. Any of the data files containing the translational and rotational parameters computed during data processing could be accessed by PLOTIT. This program provided an easy method for selectively viewing the data produced from the walking

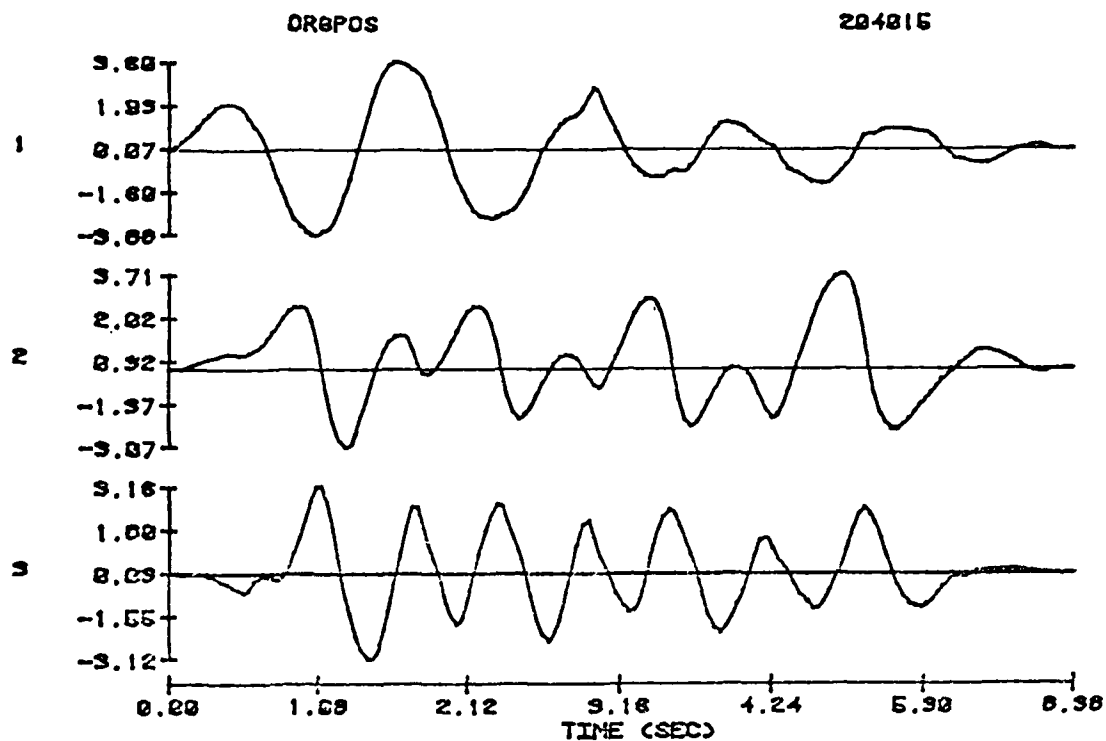


Figure 4-10. Sample Plot of Entire Data File using PLOTIT

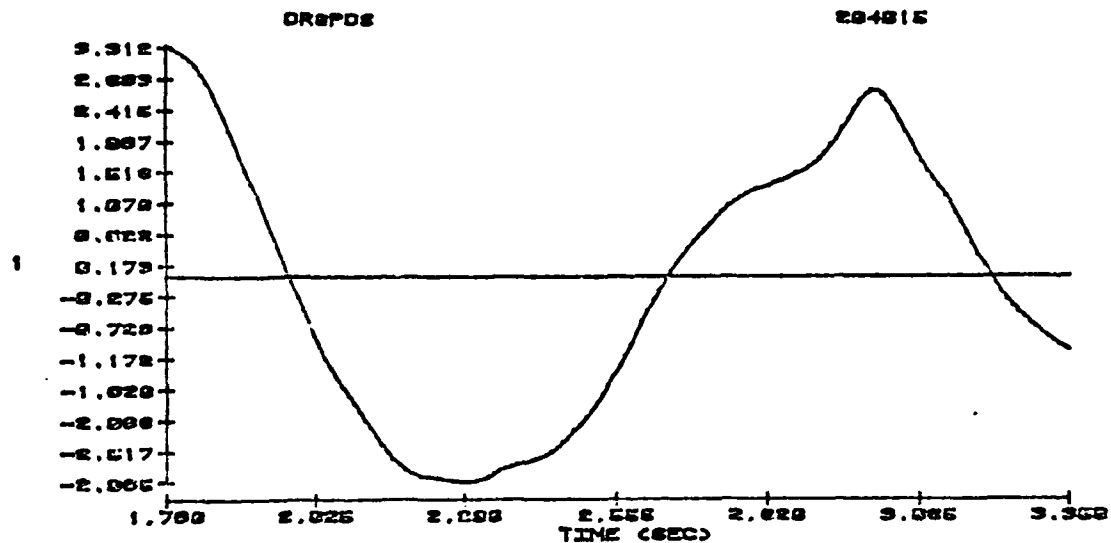


Figure 4-11. Sample Plot of Single Cycle using PLOTIT

tests. A sample plot of an entire walking section of data is shown in Figure 4-10, while a single step cycle from the same data is shown in Figure 4-11. A complete set of plots of all the data files for one subject produced using this data processing method are contained in Appendix G.

A discussion of the mathematical methods used to perform the integration and filtering of data files during data processing is presented in the following section.

4.5 Mathematical Methods used in Data Processing

The implementation of the theoretical analysis presented in chapter 2 required the integration of four sets of differential equations. An investigation was made of commonly used methods for solving first-order systems of differential equations; the Runge-Kutta method, Adams-Moulton and other "predictor-corrector" methods, and the extrapolation or Richardsonian methods. The primary considerations in selecting an integration method were stability and accuracy of the solution and the efficiency of the method when programmed for use on the digital computer. A detailed explanation of these methods may be found in Hamming(1962), Scarborough(1966) or Acton(1970).

Most integration methods are based on extrapolating the solution forward from a present known solution, the initial condition. The Runge-Kutta method starts from a known value and then, by evaluating a series of derivative values, forms a weighted average slope. The next value is then computed by multiplying the slope by the step size, or interval, and adding this product to the previous known value. The solution over a given time period proceeds by "marching" from one value to the next, always assuming that the previously computed value was correct. There is no internal accuracy check for the Runge-Kutta method, however the accuracy of the method is dependent on the step size and can be estimated. The equations for the Runge-Kutta method and its accuracy can be found in most calculus or numerical methods textbooks, Scarborough(1966). The method is not very efficient due to the large number of evaluations of the

differential equations which are required. Acton summarizes the weaknesses of this method and states:

"In either case the arguments against Runge-Kutta are formidable. It should be used only to get starting values, which it does very well."

In contrast to the Runge-Kutta method, which assumes the computed solution is correct, the predictor-corrector methods use the past history of the solution to compute the next value of the solution. The method consists of a predictor process which fits a polynomial to the three most recent derivatives of the function, extrapolates the fitted polynomial to find the next value of the derivative and then integrates (computes the area under the derivative curve) the fitted polynomial to produce the "predicted" value of the function at the next point. This predicted value is then substituted into the known differential equation to yield a new value of the derivative which has not been extrapolated. A second integration, using the new derivative, is performed to produce a "corrected" value of the function. The difference between the predicted and corrected values provide an internal measure of the error remaining in the corrected value of the function. If this difference is too large, the corrector process can be repeated, with the corrected value replacing the predicted value, until the difference becomes less than some desired tolerance. Thus, the predictor-corrector provides a "check" on how the solution is proceeding and an estimate on the accuracy of the solution.

In both the Runge-Kutta and predictor-corrector methods, the integration step size, or interval, is selected and used as long as it gives satisfactory results. It may be adjusted, but normally remains constant for long time periods during the integration process. The values produced by these methods converge mathematically to the exact solution of the differential equation as the step size approaches zero, but the step

size is never permitted to approach zero. Due to the increased computational time required by decreased step size, the numerical solution is considered acceptable if the chosen step size produces a "good" estimate of the solution.

The philosophy of the Richardsonian method is to extrapolate the step size "to the limit." In this method, several estimates of the next value of the function are generated using successively smaller step sizes. These estimates are then used to predict what the next value of the function would be if the step size had been permitted to go all the way to zero. This philosophy is very attractive, however each forward step is much more complex than either of the other methods. This method may also require many more evaluations of the differential equations at each step which increases the computational time. Its main advantage is the accuracy of the solution and with "smooth" functions the step size can be increased to relatively large values without decreasing the accuracy.

Evaluations of these three numerical integration methods were reported by Clark(1968) and Fox(1972). The objectives of these studies were to test and compare these methods on various problems for speed and accuracy. One of the systems of differential equations tested by Clark was Euler's equations of motion for rigid bodies. This set of first order, non-linear differential equations are very similar to those developed and used in this study. The results of Clark's tests showed that the Richardsonian method was preferable when a relative error of less than 10^{-5} was desired.

For this study an accuracy of 10^{-5} was considered quite sufficient and, for ease of programming, a simple, but relatively efficient, integration method was needed. Therefore, a predictor-corrector method was selected and programmed for the computer. The Adams-Moulton system, Hamming(1962), was used as the basis for subroutine AM3INM, the

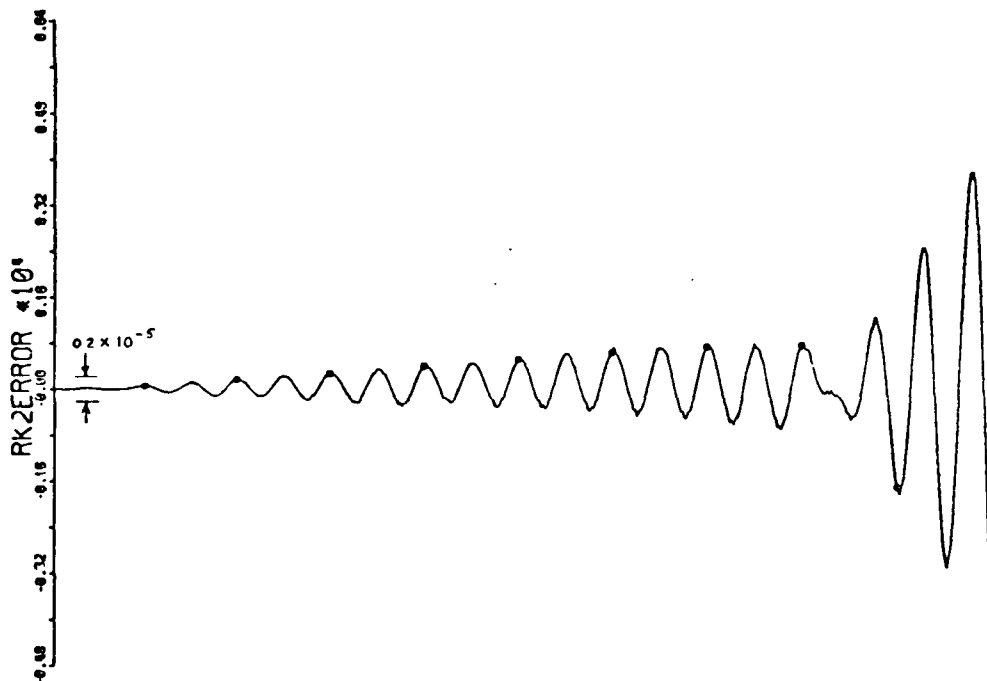
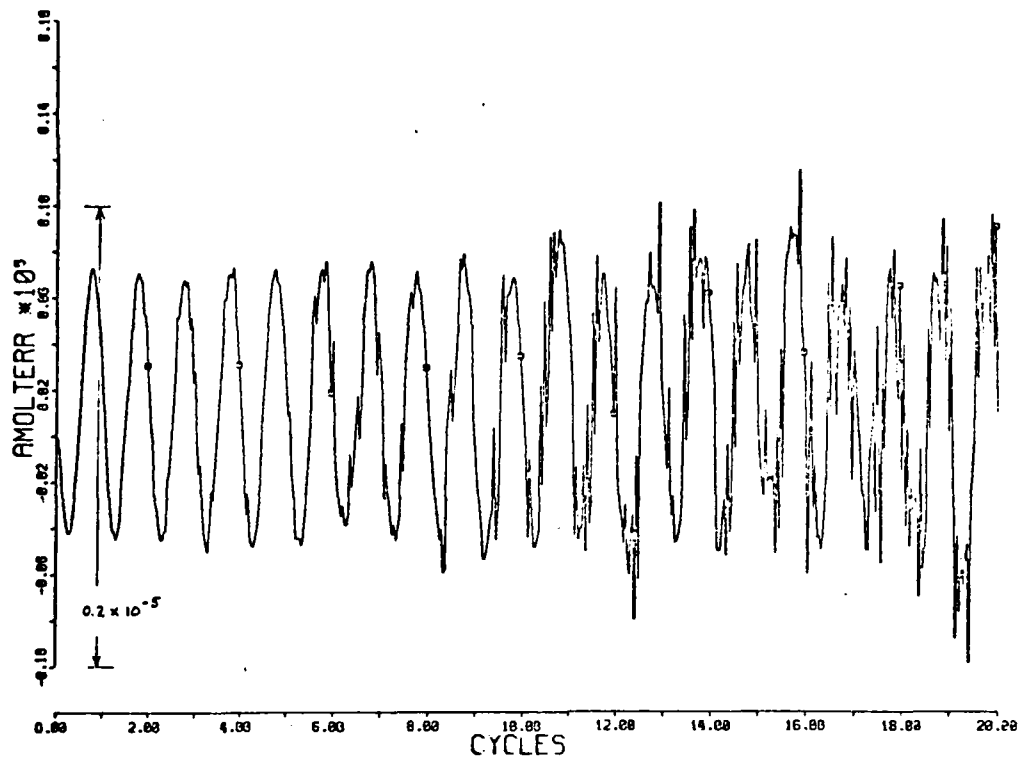


Figure 4-12. Comparison of Runge-Kutta and Adams-Moulton Integration Errors.

integration routine called by all integrating programs during data processing. This subroutine required the set of differential equations, which were to be solved, to be stored in a separate subroutine which was then called by AM3INM. A complete listing for AM3INM and the three differential equations subroutines(DIOMGM, DIANGL and DIRDOT) are contained in Appendix F.

As a test of the Runge-Kutta and Adams-Moulton methods, twenty cycles of the differential equation

$$\dot{x}(t) = a \omega \cos(\omega t) \quad (4.1)$$

with $\omega = 6.28$ rad/sec and variable amplitude, a , were integrated and compared with the analytical solution

$$x(t) = a \sin(\omega t). \quad (4.2)$$

A sampling rate of 200 Hz. was used to simulate the data sampling rate used in the data collection process. These tests clearly demonstrated the superior accuracy of the Adams-Moulton method. A typical plot of the integration errors of the two methods is shown in Figure 4-12. The differences in scale and the instability of the Runge-Kutta method, beginning at cycle 17, should be noted. Both methods required approximately the same amount of computer time to complete the integration process.

The initial conditions, or starting values, for the first data point must be known before the integration process can begin. Therefore, the initial conditions for the angular velocity, orientation angles, acceleration, velocity and position of the pelvis had to be known for each walking test. For this reason, the initial data was recorded with the subject standing in a stationary position. Since the pelvis was stationary, the initial values for the angular velocity, acceleration, and velocity were assumed to be zero. It was also assumed that no translation was required to bring the body-centered coordinate system into coincidence

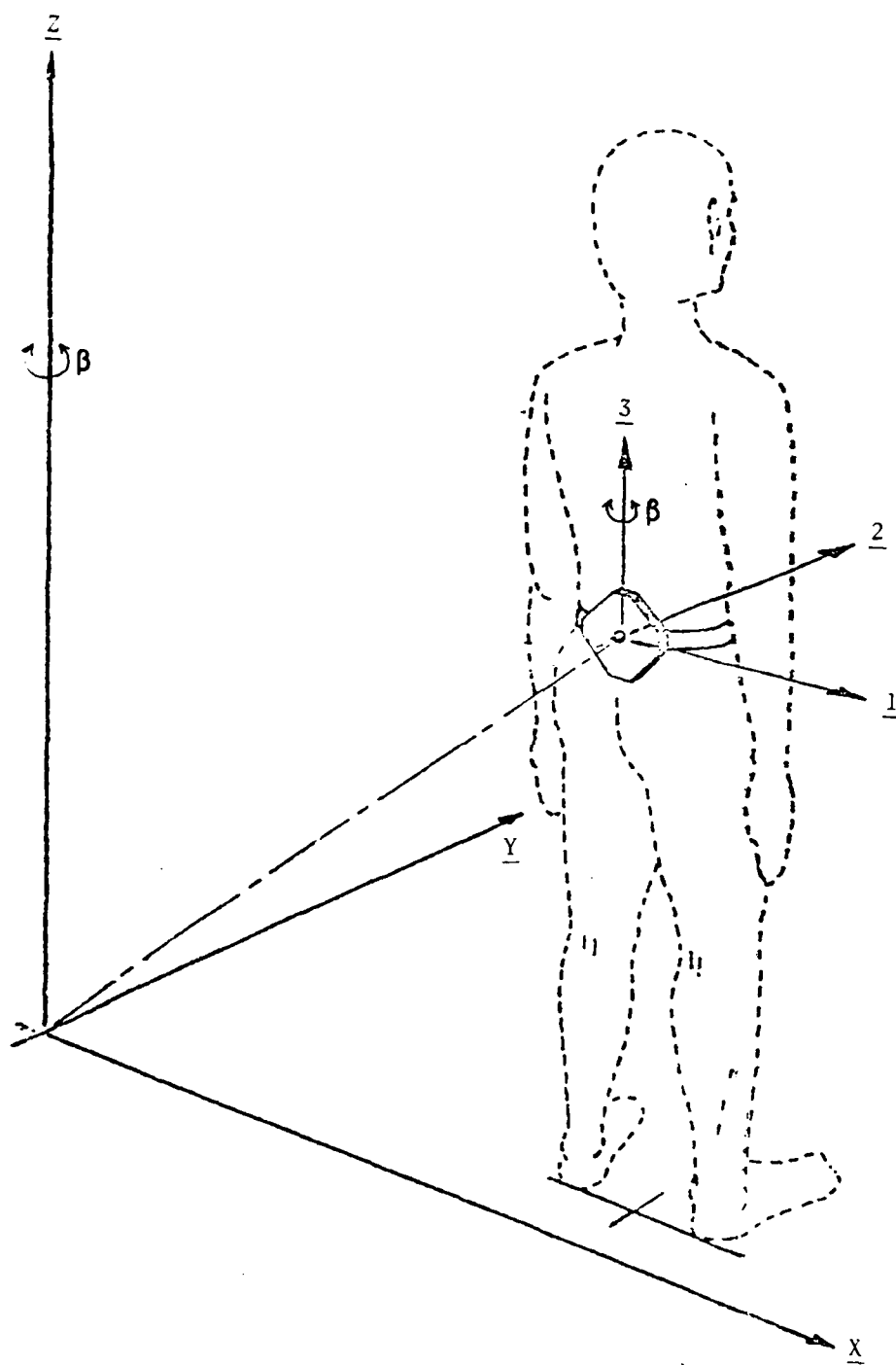


Figure 4-13. Rotation About the \underline{Z} Axis Equivalent to the Subject Changing Direction.

with the fixed coordinate system and thus, the initial values of the position were also zero. Only the initial orientation angles of the pelvis had to be computed.

These initial angles were computed from the accelerometer outputs recorded during the initial standing phase. These outputs were determined by the orientation of the sensitive axis of the accelerometer with respect to the gravity vector ($\underline{g} = -1\underline{z}$) in the fixed coordinate system. The gravitational vector, in the body-centered system, can be computed from

$$\underline{g}_B = C_B^R \underline{g}_R \quad (4.3)$$

where,

\underline{g}_B = gravity vector in body-centered coordinate frame

C_B^R = inverse of the transformation matrix, equation (2.46)

$$\underline{g}_R = \begin{Bmatrix} 0 \\ 0 \\ -1 \end{Bmatrix} \quad \text{gravity vector in the fixed coordinate system}$$

Performing the matrix multiplication indicated in equation (4.3) yields

$$\underline{g}_B = \begin{Bmatrix} -\sin \theta \cos \phi \\ \sin \phi \\ -\cos \theta \cos \phi \end{Bmatrix} \quad (4.4)$$

Therefore, the accelerometer outputs during standing are:

$$a_1 = -\sin \theta \cos \phi \quad [\text{sensitive axis along } \underline{1}] \quad (4.5)$$

$$a_2 = \sin \phi \quad [\text{sensitive axis along } \underline{2}] \quad (4.6)$$

$$a_3 = -\cos \theta \cos \phi \quad [\text{sensitive axis along } \underline{3}] \quad (4.7)$$

It is significant to note that angle β is missing from the above equations. Recall that the last rotation of the body-centered system, to bring it into coincidence with the fixed system, was through angle β about the \underline{z} axis. Conversely, the first rotation of the fixed system, to bring it into coincidence with the body-centered system, was through angle β

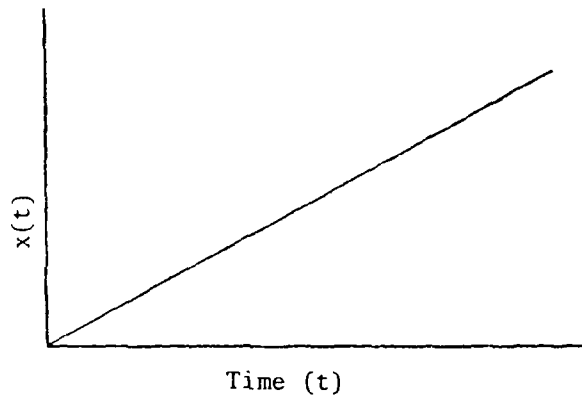


Figure 4-14. The Integral of a Constant

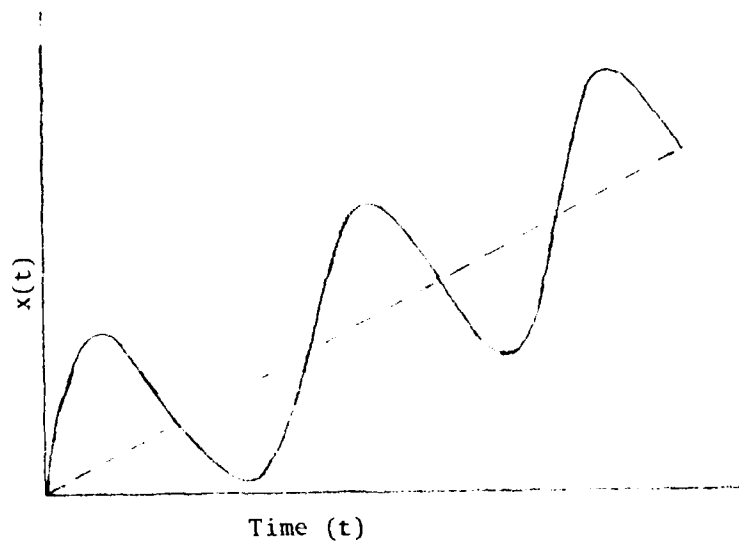


Figure 4-15. The Integral of a Periodic Function with Constant Zero Offset

about the Z axis, as shown in Figure 4-13. If the body-centered system is initially aligned with the fixed system, then all accelerometers are either horizontal or vertical and output 0 or -1 g. A rotation about the Z axis will not effect any of the accelerometer outputs since the gravitational vector is aligned with the Z axis. The rotation sequence used in this study resulted in a more generalized solution than the normal Euler angle sequence in that the subject did not have to stand or walk in any particular direction. If the initial value of β was assumed to be zero, this resulted in the Y axis being located in the direction the subject was facing. The subjects were free to select the direction in which they began to walk and were not restricted to following a line on the floor representing the Y axis. The Y axis, for computational purposes, was automatically set to the direction the subject selected during the initial standing phase.

The computer program INANGL solved equations (4.5), (4.6) and (4.7) for the initial angles ϕ and θ and set the initial value of β to zero. The input data to INANGL were the average outputs of all accelerometers oriented in one particular measurement direction. These were computed in the statistics program, STADAT, and stored in data file COSTAT.DAT.

If a small error, in zero offset, was present in the initial conditions, errors could be produced in the solution by the integration process. The integral of a constant is a ramp function, shown in Figure 4-14. Therefore, if a small offset error was present in the initial conditions of a periodic function which was to be integrated, the output would appear with a ramp function superimposed on the solution as shown in

Figure 4-15. If a set of non-linear, or cross-coupled, differential equations were integrated, then offset errors could introduce low frequency errors rather than the simple ramp function. It would be extremely

difficult to eliminate all offset errors and therefore a digital bandpass filter was used after every integration to remove any low frequency errors in the solution.

The digital filter used in this study was a recursive, eighth order, Butterworth bandpass filter, Hamming(1977). The filter was programmed as subroutine BNDPAS and was called by all the filtering programs during data processing. The bandpass frequencies were entered when the filter program was run which allowed these frequencies to be adjusted for each specific filtering operation. A recursive filter was used to eliminate any phase shift in the output caused by the filtering process. Butterworth filters (and most other filters) are not symmetric and therefore the phase relation between output and input is not the same for all frequencies. The recursive filter eliminates the phase shift by processing the data in the forward direction and then reprocessing the output in the reverse direction. If there is a phase shift at a given frequency, produced in the forward pass through the filter, the same phase shift, with opposite sign at the same frequency, is produced in the reverse direction. Therefore, the two phase shifts exactly cancel when the output of the forward direction pass is reprocessed in the reverse direction.

For the angular velocity, acceleration and velocity integrations, the filtering of the integrated output was followed by programs to compute the mean value of the integrated data. If the mean value was not zero, then the computed mean was subtracted from the integrated data to ensure that the mean of the integrated data was zero prior to beginning integration of the next variable in the sequence. For example, programs FILVEL, VEMEAN and ADJVEL were run following the integration of the acceleration data. Low frequency errors in the velocity data output by this integration were removed by FILVEL. The mean values of the data were computed by VEMEAN and then adjusted to zero by ADJVEL. This process minimized any offset errors

present in the velocity data before it was integrated to produce position data. This method was only implemented when the initial conditions for the following integration were assumed to be zero and proved to be very effective in eliminating integration errors caused by zero offset error.

The testing performed on the measurement system and the data processing method will be discussed in the following section.

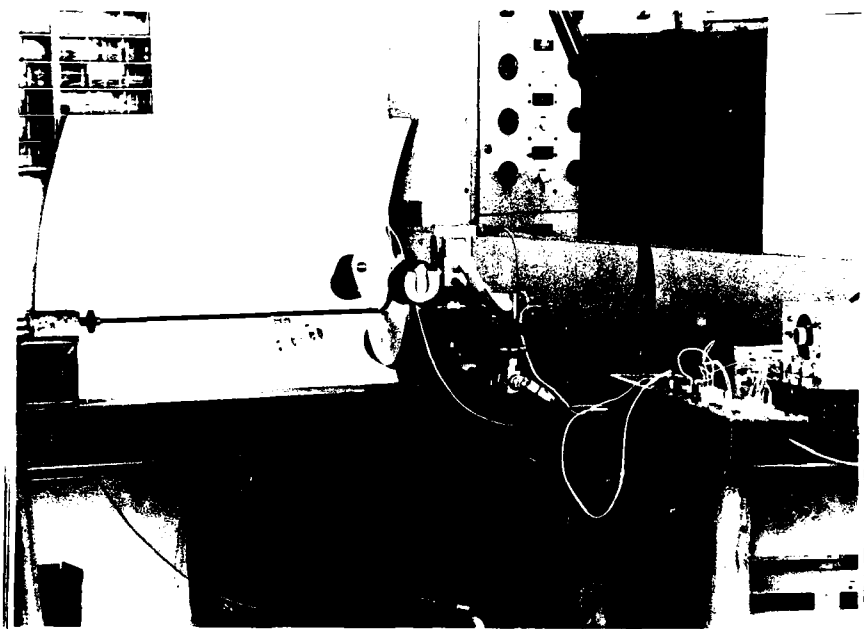


Figure 4-16. Hydraulic Bench Test Apparatus.

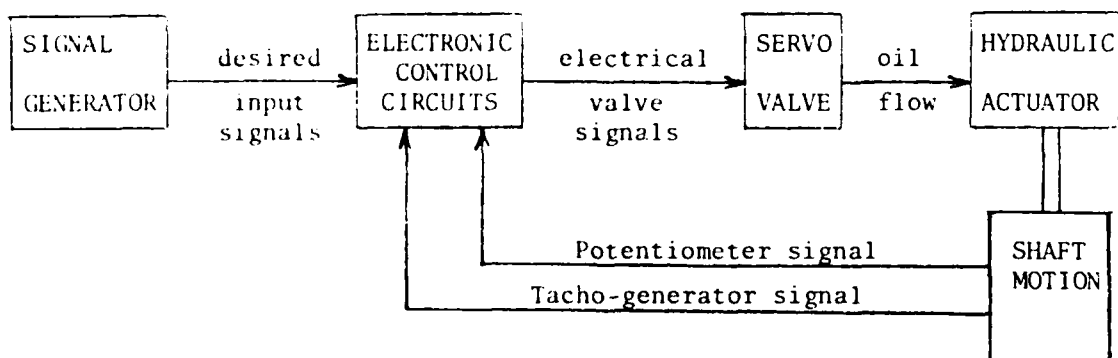


Figure 4-17. Hydraulic Bench Apparatus Block Diagram.

4.6 Testing of the Experimental Method

The accelerometer measurement system, and its associated data processing programs, developed in this study was tested experimentally to compare it with other kinematic measurement systems. Experimental verification of the method was used because a generalized theoretical verification is virtually impossible. The non-linear differential equations developed in this study have no known analytical solution. Therefore, it is impossible to specify input variables which can be processed and then compared with a known solution to estimate the accuracy of the computing method. It is also impossible to track the propagation of errors in accelerometer alignment, cross-axis sensitivity, etc. through the complex theoretical equations which were developed in chapter 2 with any degree of confidence in the results. In addition, the experimental comparisons were made based on the results obtained from data processing and therefore any differences include all error sources present in the equipment and data processing method. Two tests were conducted: the first tested the systems effectiveness in computing rotational parameters, the angular velocity and angular position, and the second compared the translational displacements computed by the accelerometer method with those measured by the traditional cinephotographic method.

The rotational test was performed with a hydraulic bench apparatus (electrohydraulic servomechanism system) located in the Control Electronics Laboratory of the Engineering Science Department at Oxford University. This apparatus, shown in Figure 4-16, consisted of a shaft which was rotated by a hydraulic actuator. The operation of the hydraulic actuator was controlled electrically. A simplified block diagram of the system is shown in Figure 4-17. The signal generator was adjusted to input the desired motion, in the form of a voltage signal, to the electronic control circuits. The control circuits produced the necessary electronic

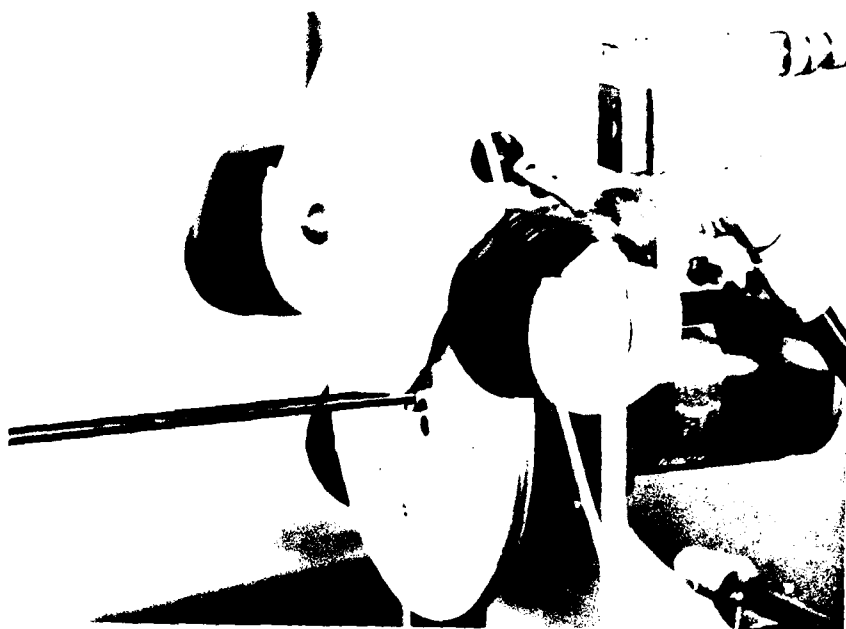


Figure 4-18. Accelerometer Body Mount Installed on Hydraulic Bench Shaft.

signals for the servo valve which controlled the flow of oil to the hydraulic actuator. The oil flowing through the hydraulic actuator caused the shaft to rotate. A potentiometer and tacho-generator measured the angular position and angular velocity of the shaft. These two outputs, "feedback" signals describing the actual motion of the shaft, were used by the control circuits to adjust the electrical servo valve signals to ensure that the actual shaft motion closely matched the desired motion. This explanation has been brief and simple, but should provide sufficient information to understand the test procedure.

The accelerometer body mount was securely attached to an aluminum disc mounted on the shaft, shown in Figure 4-18. In this position, the body mount rotated about the z axis when the shaft was rotating. The accelerometers had been temperature stabilized and calibrated, using the method previously described, before being mounted on the shaft. The signal generator was adjusted to produce a sinusoidal oscillation of the shaft and the amplitude of the oscillation was adjusted by increasing or decreasing the output voltage. The output signals from the accelerometer difference amplifiers, the potentiometer(measured angular position of the shaft) and the tacho-generator(measured angular velocity of the shaft) were recorded on a six channel tape recorder for playback into the computer.

Three rotation tests were performed and each consisted of starting the shaft oscillating from a stationary position, recording the output signals for 10 to 15 seconds and then stopping the oscillation. The signal generator voltage level was adjusted to produce $\pm 2.5^\circ$, $\pm 6^\circ$ and $\pm 12^\circ$ oscillations of the shaft. After the test data were recorded, the accelerometer body mount was removed and the accelerometers were recalibrated. The mean values of the before and after test calibrations were used as the accelerometer scale factors and offsets in data

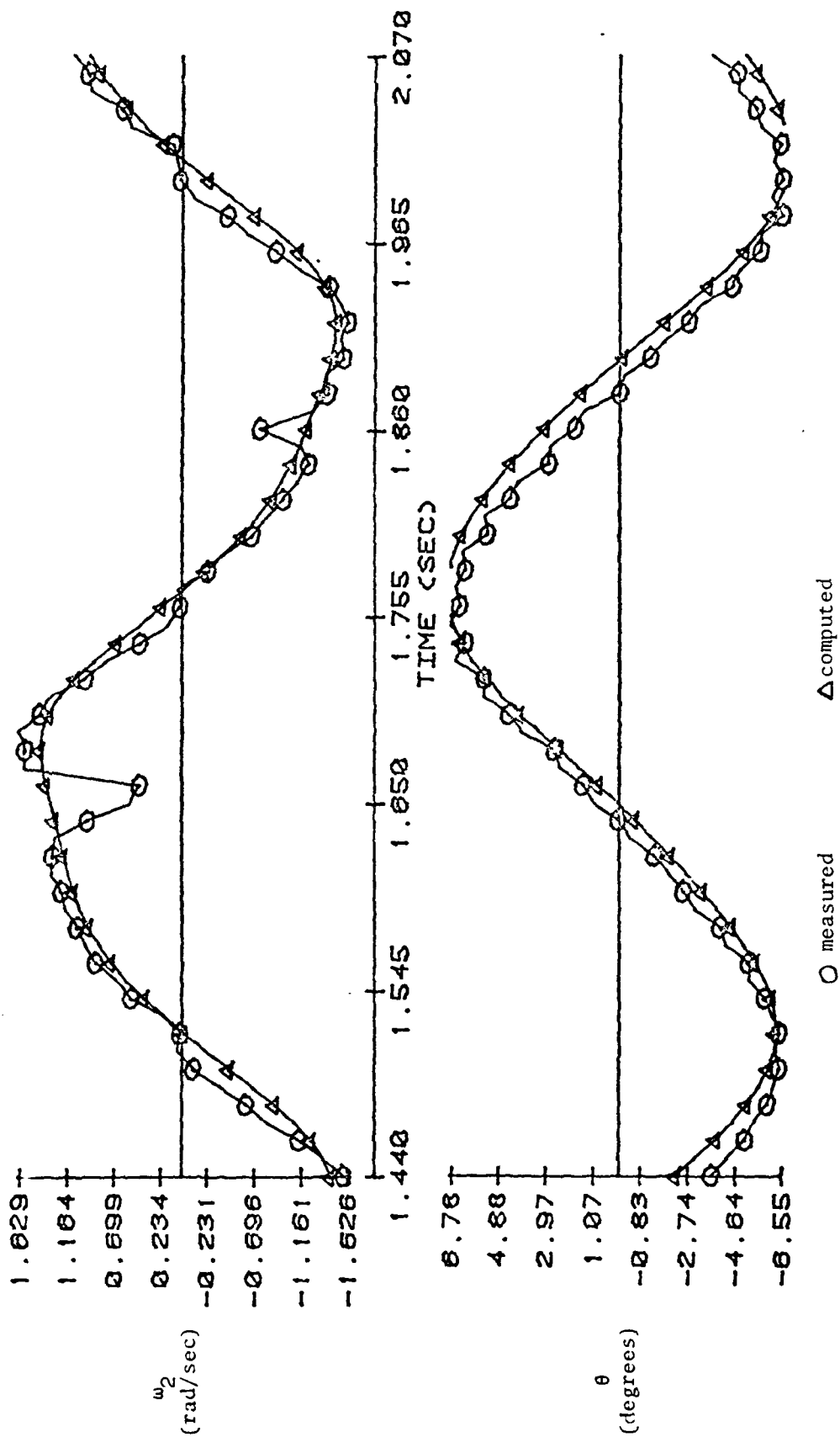


Figure 4-19. Hydraulic Bench Test Results for One Cycle.

processing. The scale factors of the potentiometer and tacho-generator were measured and found to be -3.82 volts/radian and -0.237 volts/radian/second respectively.

The data recorded during the tests was then stored on the computer and the accelerometer data were processed using the programs necessary to produce the angular velocity and angular position. The potentiometer and tacho-generator voltages were converted to degrees and radians/second using the measured scale factors. The results were then plotted and the mean absolute differences between the measured and computed rotations were calculated. The graphical results of a single cycle of one test are shown in Figure 4-19. The complete graphical results of all three tests are contained in Appendix H. The mean absolute differences between the measured and computed angular velocities for the three tests were 0.079, 0.163 and 0.295 radians/second. The corresponding peak to peak amplitudes were 1.26, 3.24 and 7.37 radians/second and therefore the mean difference between the measured and computed angular velocity was less than 6.2% of the peak to peak amplitude. Similarly, the mean absolute differences between the measured and computed angular position were 0.33° , 0.81° and 1.62° . The corresponding peak to peak amplitudes were 5.6° , 13.6° and 28.6° . The mean difference between the measured and computed angular position was less than 6.0% of the peak to peak amplitude for the three tests. These results indicated that the accelerometer system developed in this study could measure the angular velocity and angular position to within 7% of the peak to peak amplitude of the motion.

Translational displacements computed by the accelerometer method and the traditional cinephotographic method were used to assess the accelerometer measurement systems effectiveness in determining the translational parameters. In this test, black skin markers, normally placed on anatomical landmarks, were attached to the accelerometer body

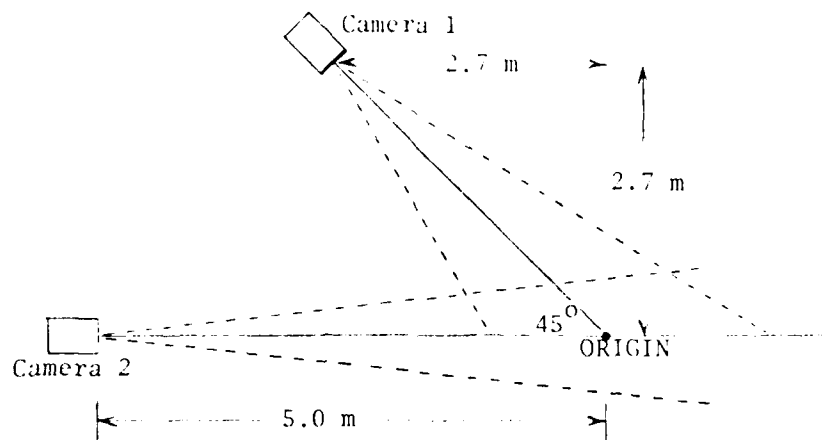


Figure 4-20. Cine Camera Locations.

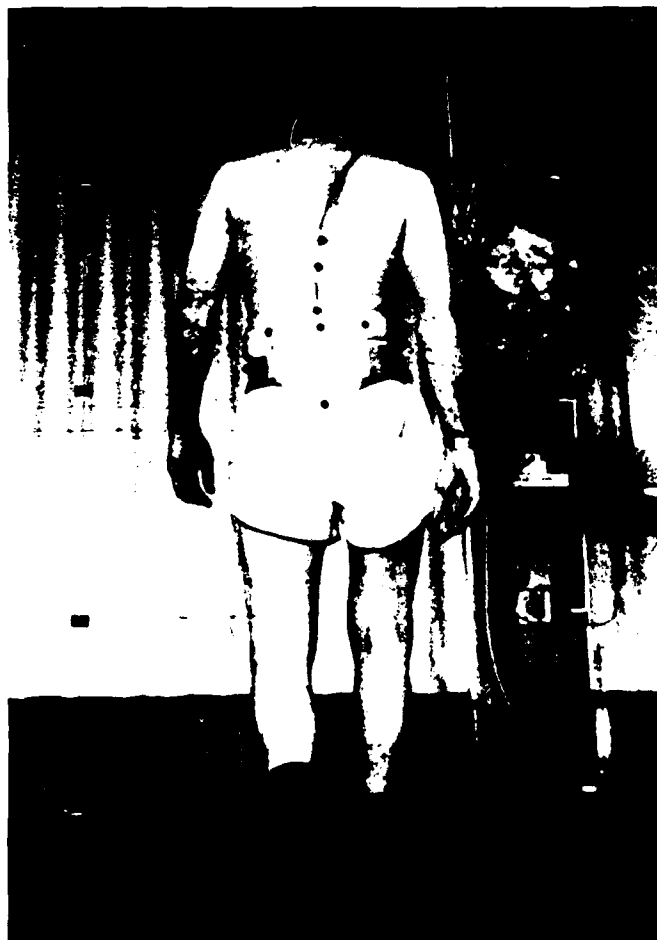


Figure 4-21. Projected Frame of Cine Film.

mount. A basic walking test sequence was conducted on a male subject with simultaneous recording of the walk on 16mm cine film with two cine cameras.

The cinephotography method used in this test was developed by Miss L. Huntington for use in the OOEK gait laboratory. Two high speed Bollex cine cameras were located as shown in Figure 4-20. To describe the coordinates of filmed markers in three dimensions, it was necessary to have two projective observations for each marker and a knowledge of the camera parameters, e.g. focal length, position, attitude and image distortion. The camera system was calibrated using a three-dimensional target system which consisted of four targets on each of nine vertically hanging threads. The threads were positioned so that the cameras could be aligned properly using the principles of parallax. Using the known calibration target distances and the distances between calibration targets on the projected image (from the processed cine film), the focal length of the camera/projector system was calculated. Estimates of the image distortion were made by filming a grid of known dimensions and measuring the distortion on the projected image.

After filming the calibration targets, the subject was filmed walking, with the accelerometer body mount in place, by the cine cameras running synchronously at 50 frames/second. Three walking tests were performed in which cine filming and accelerometer data recording were accomplished simultaneously. The cine films were developed and then projected through an analyzing projector onto a digitizing table. One frame of cine film, being projected, is shown in Figure 4-21. The necessary camera/projector system parameters were determined by digitizing the projected calibration targets located on the first few frames of the cine film. The projected body mount marker coordinates were then digitized for each time interval during one step cycle. Using computer analysis, the

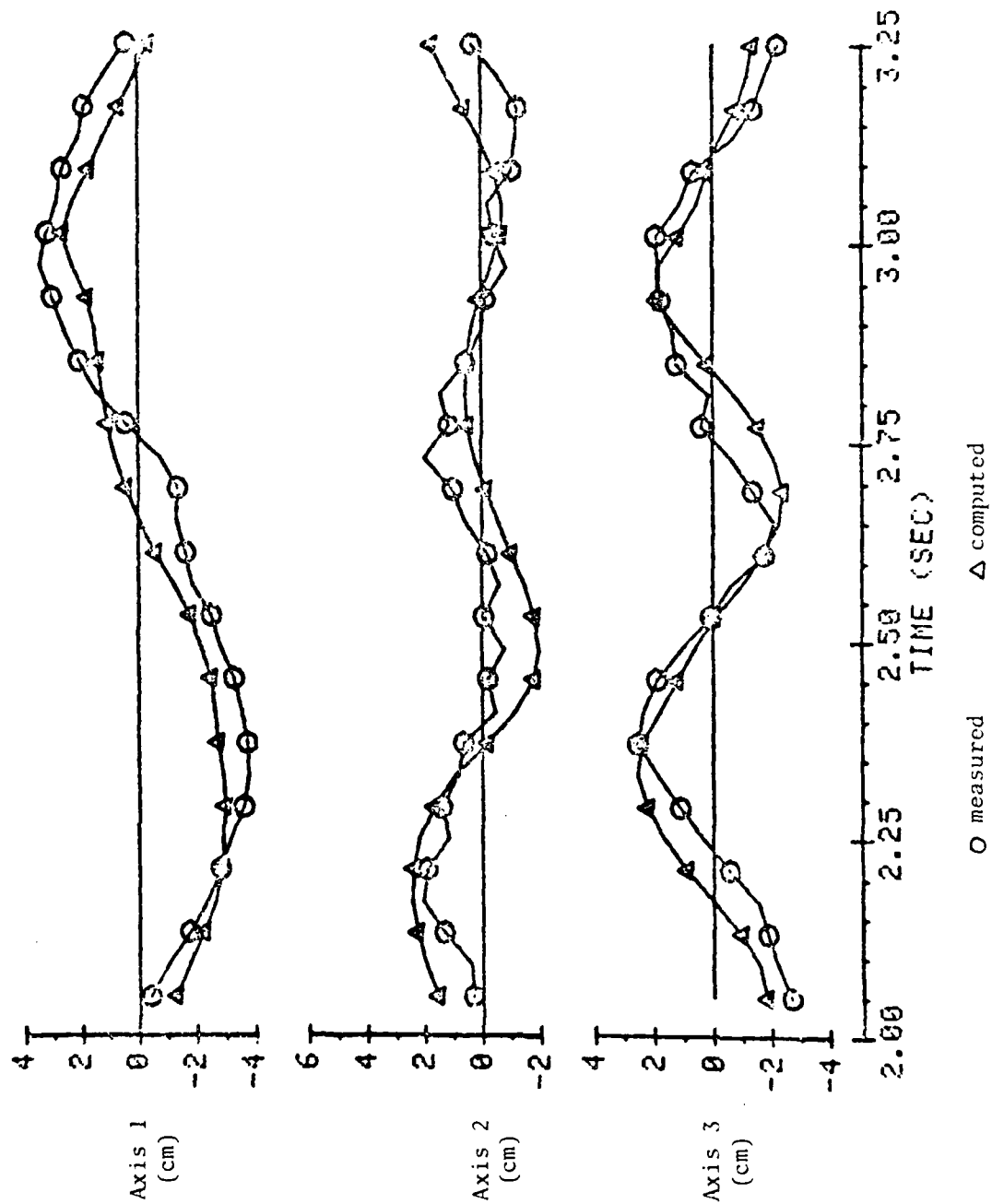


Figure 4-22. Cine Film Walking Test Displacement Results.

three dimensional coordinates of the body mount markers, corrected for distortion, were calculated for one step cycle from each of the three walking tests.

As it was physically impossible to place a skin marker at the origin of the accelerometer body mount, markers were located 8 cm above and 8 cm below the origin. After obtaining the coordinates of these markers from the cine film analysis programs, the origin location was determined by computing the midpoint location between the two markers. The three dimensional location of this midpoint, calculated using cinephotography, could then be compared to the location of the origin of the body mount, calculated using the accelerometer method. Because the accelerometer method computed relative displacements and the cinephotography method computed absolute(in terms of its fixed reference system) displacements, the cinephotography coordinates were modified to yield relative displacements. This was accomplished by subtracting a constant offset from the 3 axis data, representing the height above the floor, and a ramp function from the 2 axis data, representing the distance walked in the plane of progression.

A graphical comparison of the cinephotography and accelerometer displacement data for one walking test is shown in Figure 4-22. The results for the other two walking tests are contained in Appendix H. The mean absolute differences(in mm) between the two methods for the three step cycles analyzed were:

| | <u>Walk 1</u> | <u>Walk 2</u> | <u>Walk 3</u> |
|-------------------------------|---------------|---------------|---------------|
| Axis 1(right hand direction) | 13.4 | 8.2 | 9.6 |
| Axis 2(progression direction) | 18.0 | 9.0 | 18.4 |
| Axis 3(vertical direction) | 6.8 | 7.2 | 8.1 |

From this test one could only conclude that the two methods produced comparable results for translational displacement as no precise accuracy was available for either method.

In the following chapter the results of the walking tests, using the accelerometer measurement system developed in this study, conducted on male and female subjects will be presented.

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CHAPTER 5

EXPERIMENTAL RESULTS

- 5.1 Introduction
- 5.2 Method of Presenting the Experimental Results
- 5.3 Rotational Results
 - 5.3.1 Pelvic Rotation Results: Normal Females
 - 5.3.2 Pelvic Rotation Results: Normal Males
 - 5.3.3 Pelvic Rotation Results: Normal Females in High Heels
 - 5.3.4 Pelvic Rotation Results: Normal Males with Back Load
- 5.4 Translational Results
 - 5.4.1 Pelvic Translation Results: Normal Females
 - 5.4.2 Pelvic Translation Results: Normal Males
 - 5.4.3 Pelvic Translation Results: Normal Females in High Heels
 - 5.4.4 Pelvic Translation Results: Normal Males with Back Load

5.1 Introduction

The experimental results obtained by measuring and processing data using the procedures outlined in the previous chapters are presented in this chapter. A discussion of the method used to present the results is contained in the first section. The remaining sections contain the rotational and translational results obtained for each of the walking tests conducted in this study.

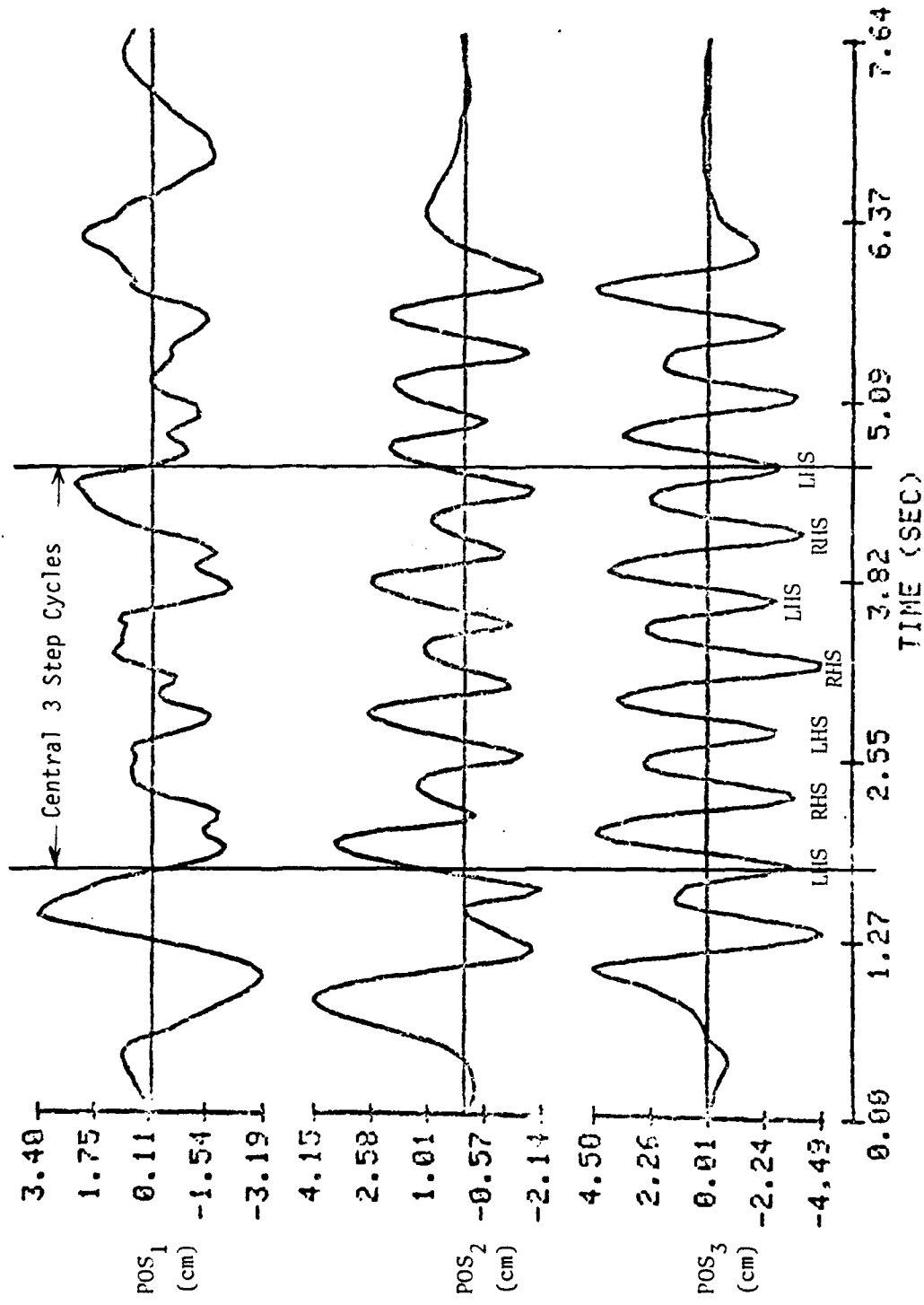


Figure 5-1. Typical Walking Test Position Data Showing the 3 Step Cycles Selected for Analysis.

5.2 Method of Presenting the Experimental Results

The experimental results obtained during this study were presented in graphical form to permit visual observation and interpretation. The results have been limited to the central three step cycles from each of the walking tests. The subjects typically completed six to seven step cycles during one walking test; the first and last few step cycles were not included since the subjects began and ended each walking test in a stationary position. Only the central cycles of the walking test were considered representative of the normal walking pattern of the subject. A typical set of results for the complete walking test, with the central three walking cycles analyzed marked by vertical lines, is shown in Figure 5-1.

The three central step cycles were selected for analysis using computer program SCNPOS. This program scanned the vertical pelvic position data for minimum points and displayed them on the terminal screen. The time at which the minimums occurred and the data storage locations were also displayed. The operator selected the data storage locations for the beginning and end of the central three cycles and then, using program PLOTIT described in chapter 4(p. 99), displayed the position data on the terminal screen. The plot shown in Figure 5-1, without the vertical lines and heel strike labels, is typical of the display generated by PLOTIT. When the locations of the three cycles to be analyzed had been visually verified, the operator recorded the first and last data storage locations. He also insured that the first and last data points were left heel strikes by observing the right/left position of the pelvis, designated by abscissa label POS_1 . When the left heel strikes the ground the pelvis should be moving to the left side(i.e. going negative in the plot).

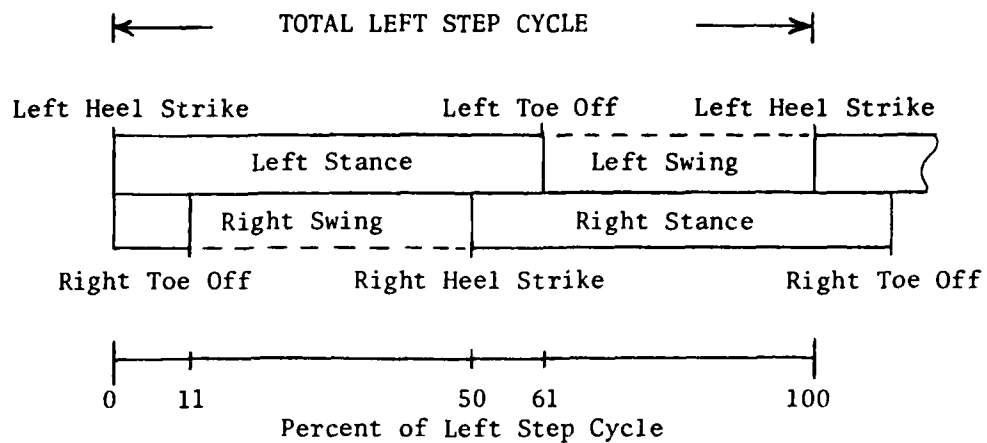


Figure 5-2. The Left Step Cycle.

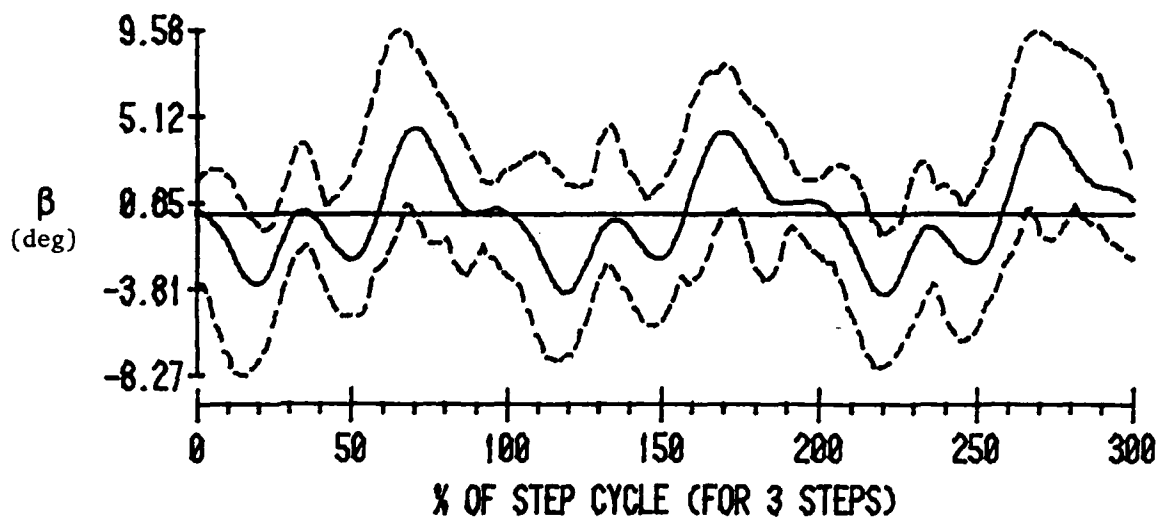


Figure 5-3. Sample Plot from the Results Sections.

One left step cycle was defined, in this study, as the cycle beginning and ending with left heel strike and is shown in Figure 5-2. The step cycle consists of a stance phase, when the left foot is in contact with the ground, and a swing phase, when the left foot is in the air. The stance phase normally amounts to 61% of the cycle and the swing phase 39%, Murray, et.al.(1966). The right heel normally strikes the ground at 50% of the cycle and the double support phase, when both feet are in contact with the ground, ends at 61% of the cycle, when left toe off occurs.

Each subject chose their own walking speed and therefore the amount of time for one step cycle was different for each subject, from 0.85 to 1.20 seconds. To reduce all data to the same scale, for comparison purposes, the ordinate scale was converted from time to percent of the left step cycle. This was accomplished by using program STORE3 which converted the data recorded for all seven subjects in one test to the same number of data points on a zero to 300% ordinate scale. This scale represented the three central step cycles stored for analysis where the appropriate step cycle event percentage carried on through three cycles, i.e. right heel strike occurred at approximately 50%, 150% and 250%.

Each plot, presented in the results sections, consists of one heavy line, representing the mean of the values computed for the seven subjects in one test, and two dashed lines, representing the maximum and minimum values. A sample of one plot from the results section is shown in Figure 5-3. All three lines together represent the mean and extreme values computed at one position in the step cycle for the seven subjects participating in one test. Therefore, the individual plots of the measured parameters for each of the seven subjects lie within the dashed lines. This method of presenting the results was chosen to reduce the volume of graphical data and yet retain the essential information.

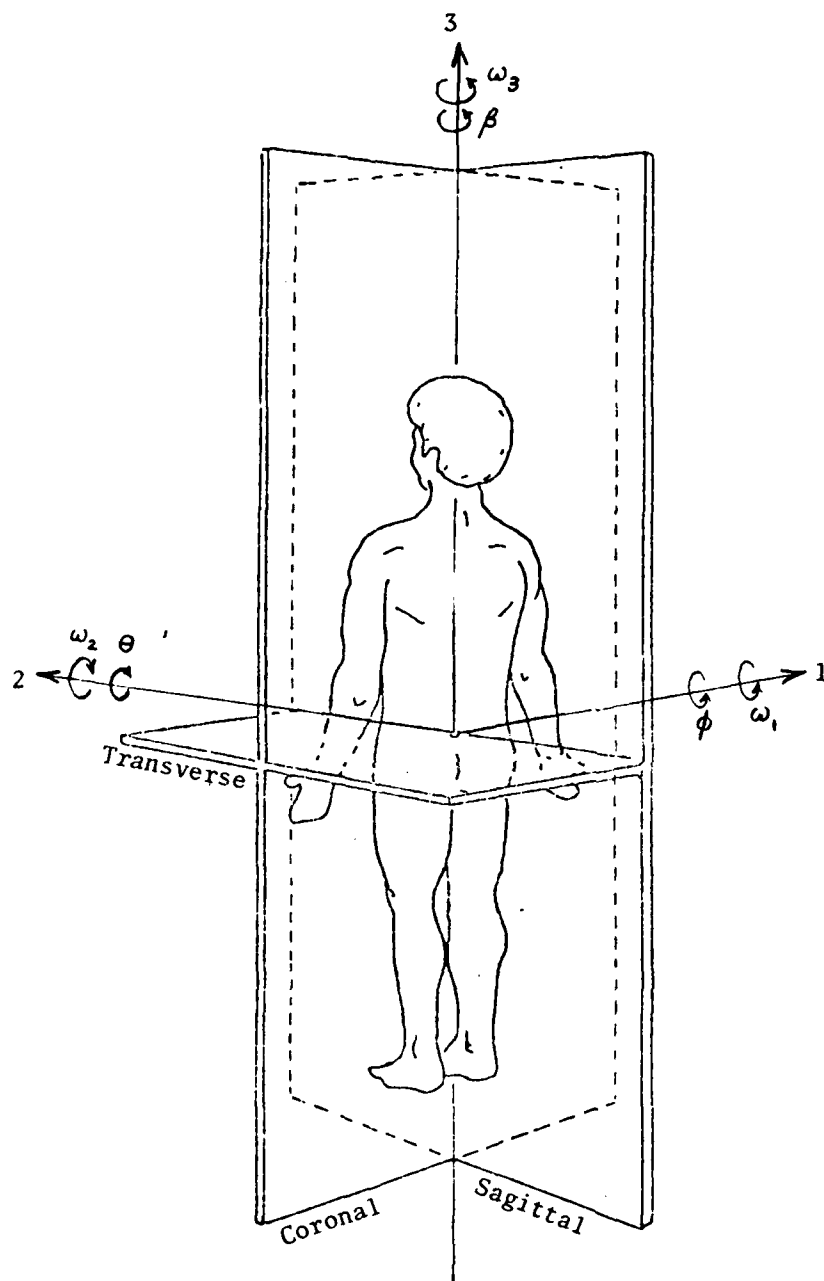


Figure 5-4. Coordinate Axes and Rotations for the Experimental Results.

The mean values, shown in the plots, should not be considered to represent a "normal" value for the tests conducted in this study. The word normal can be ambiguous when used to describe kinematic parameters since kinematic functions vary widely from individual to individual. Unless a statistical study of a large, random population of normal subjects is made, the strict mathematical definitions of mean and normal do not apply. The word normal, when used in this study, does not imply a corresponding mathematical precision, but is intended to indicate the non-mathematical, subjective use of the word normal, that is a typical result obtained from a healthy subject. Therefore, a normal result may not coincide with the mean values plotted, but would be expected to lie within the maximum and minimum ranges; deviations from the mean curve should not be classified as abnormal.

The results of each test were plotted for each of the three coordinate axis directions. The coordinate system was a fixed system with the axes and rotations shown in Figure 5-4. The axis direction is indicated in the plots as a subscript on the abscissa label. The rotational and translational motions were described by the following:

- (1) Sagittal plane rotation was about axis 1; a positive rotation occurred when the anterior section of the pelvis moved upward.
- (2) Coronal plane rotation was about axis 2; a positive rotation occurred when the right side of the pelvis moved downward.
- (3) Transverse plane rotation was about axis 3; a positive rotation occurred when the right side of the pelvis moved anteriorly.
- (4) Right/left translation was along axis 1; a positive motion occurred to the right.
- (5) Anterior/posterior translation was along axis 2; a positive motion occurred anteriorly.
- (6) Vertical translation was along axis 3; a positive motion occurred upward.

In addition to the plots, a table of the cadence and average peak to peak value of each parameter is presented. This peak to peak value was the average of the peak to peak values which occurred in the three central step cycles for each subject. A mean peak to peak value for the seven subjects is also shown in each table.

The rotational and translational results of the data measured and processed using the methods outlined in this section and chapter 4 are contained in the following sections.

5.3 Rotational Results

The following sections contain the experimental results of the angular velocity and angular position of the pelvis measured in this study. A brief description of the walking test precedes the graphical results presented in each of the following sections.

5.3.1 Pelvic Rotation Results: Normal Females

The plots and table contained in this section show the rotational results for tests of female subjects walking barefoot and in low heeled shoes. The angular velocity, $\underline{\omega}$, and the rotation angles, ϕ , θ and β , are shown for each of the three coordinate axes.

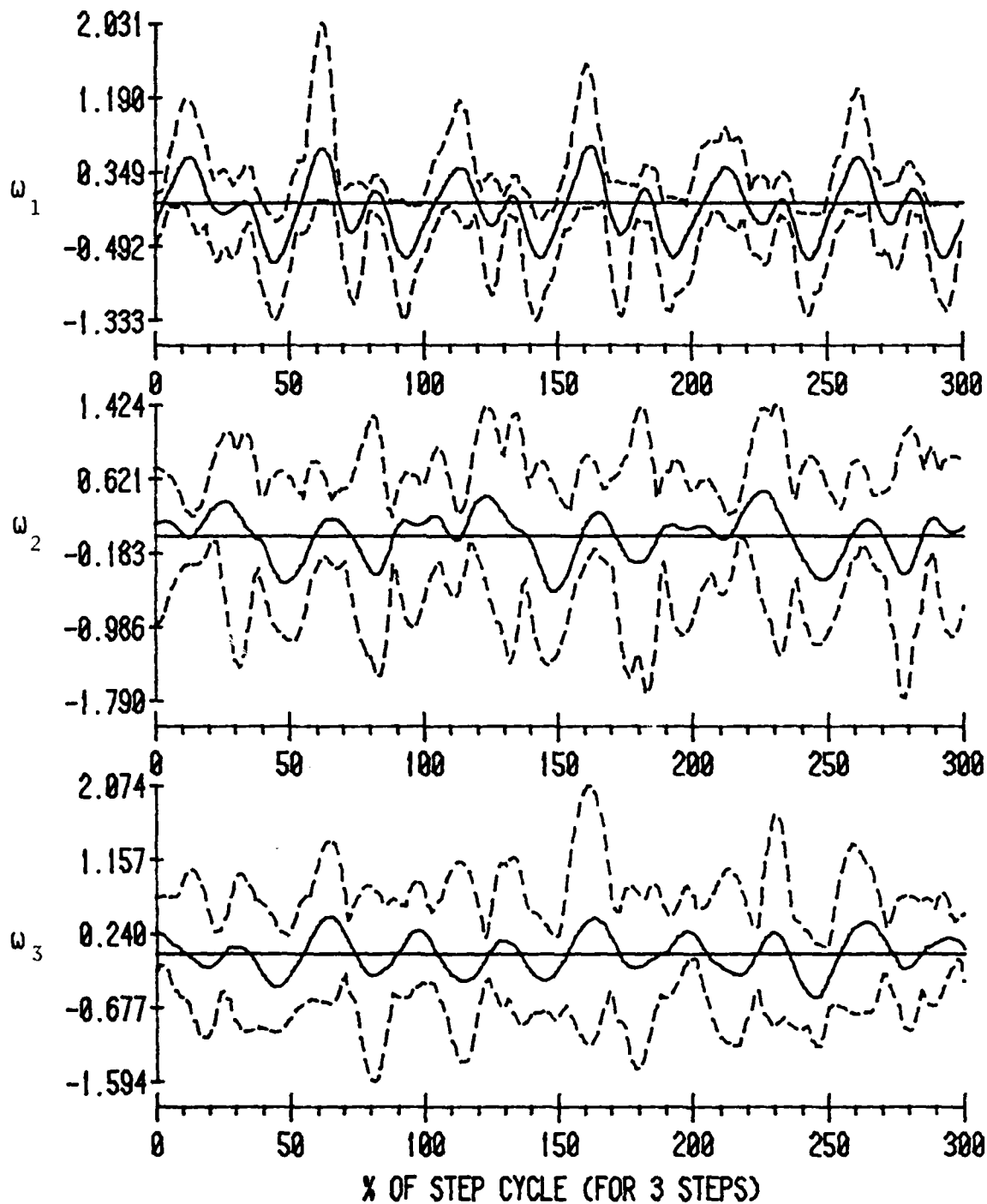


Figure 5-5. Pelvic Angular Velocity (rad/sec) for Female Subjects Walking Barefoot.

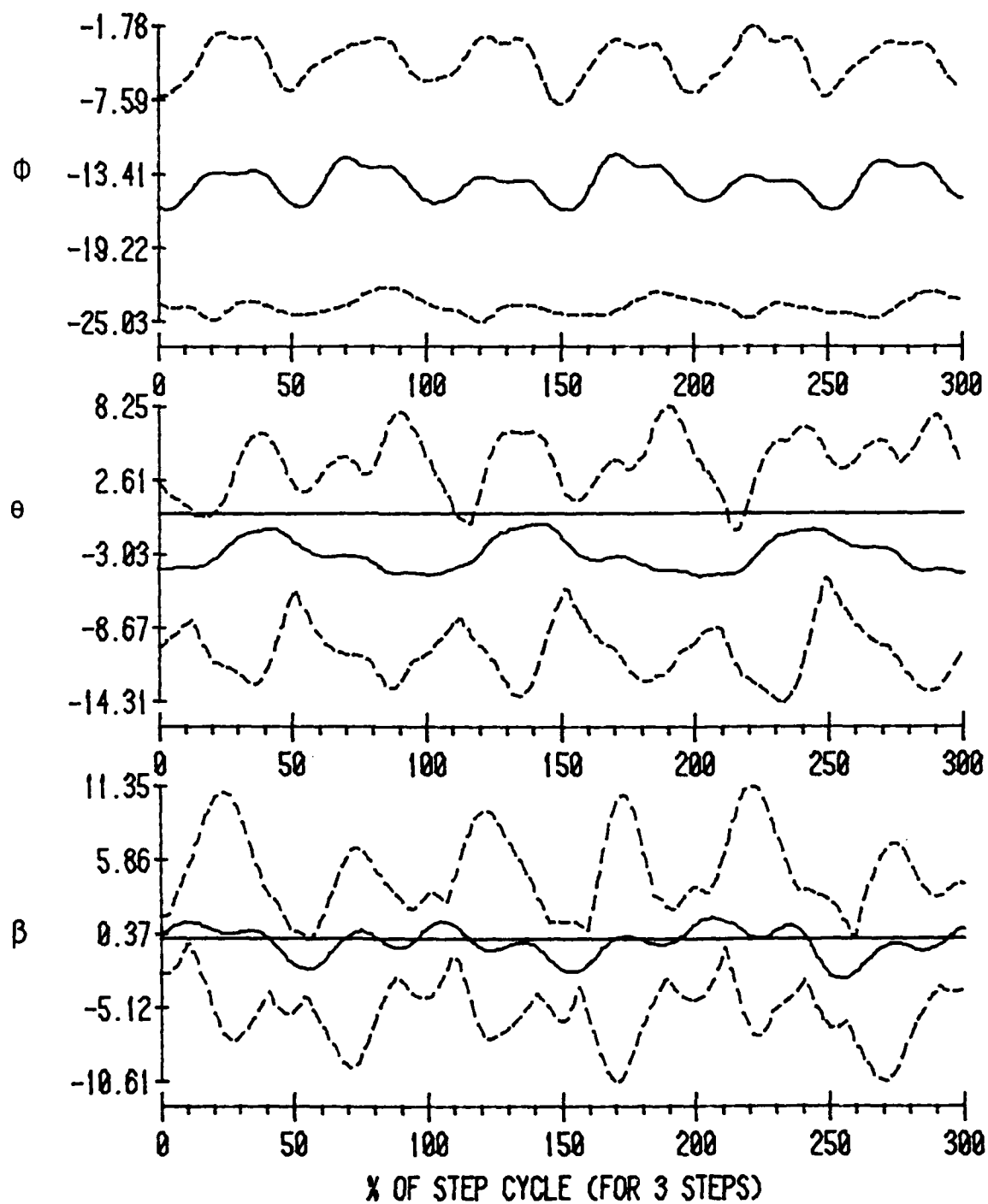


Figure 5-6. Pelvic Rotation Angles (deg) for Female Subjects Walking Barefoot.

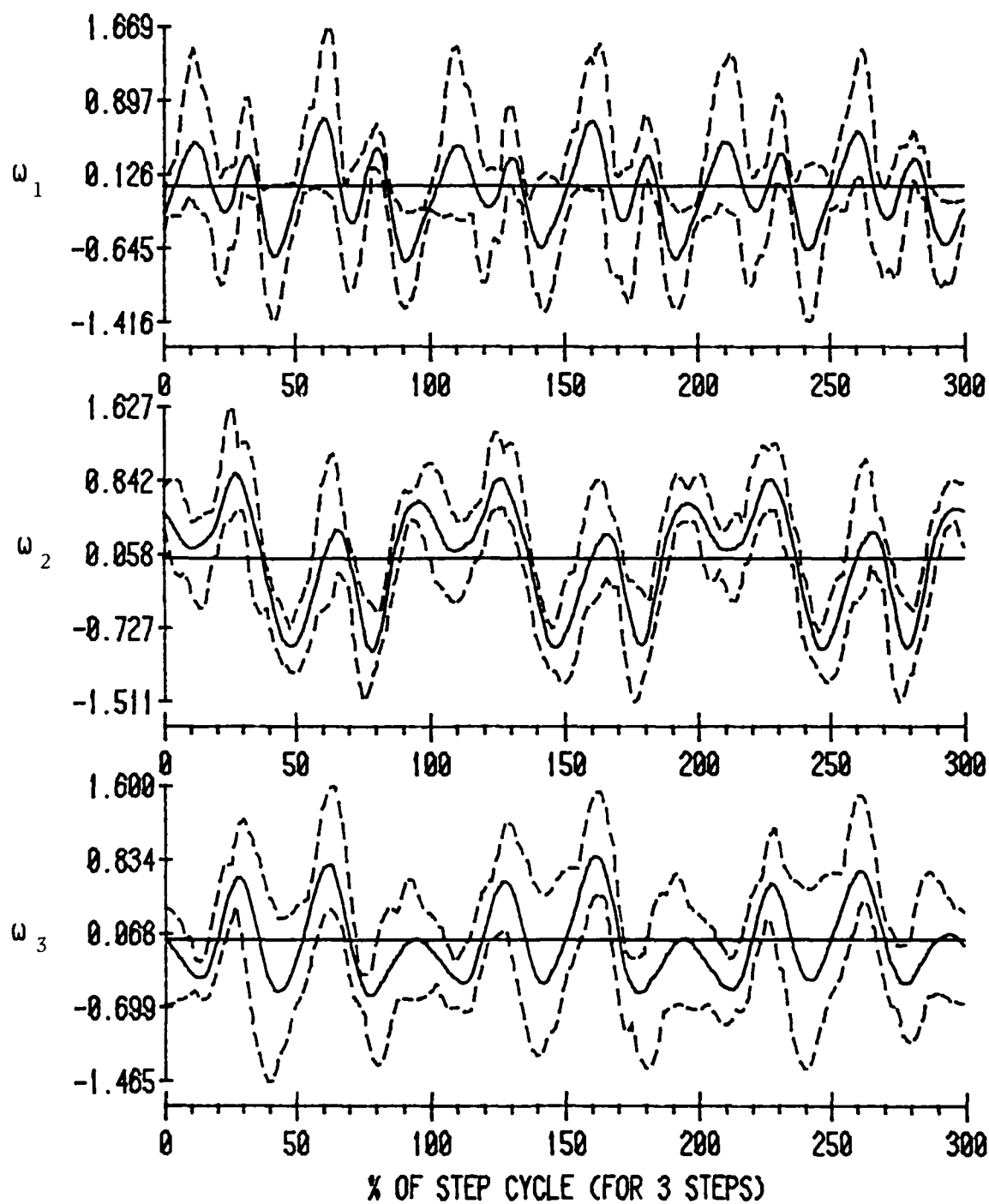


Figure 5-7. Pelvic Angular Velocity (rad/sec) for Female Subjects Walking in Low Heeled Shoes.

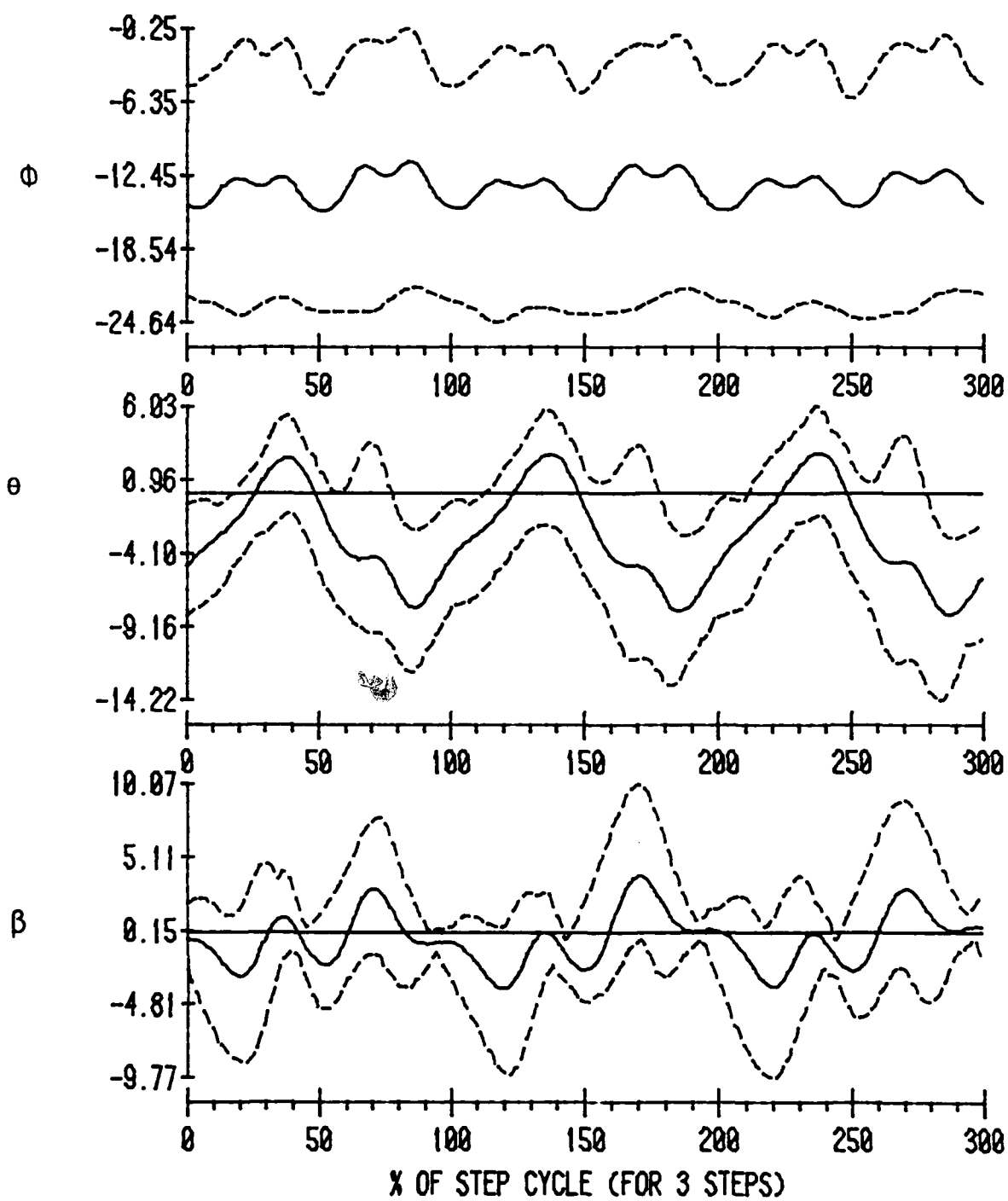


Figure 5-8. Pelvic Rotation Angles (deg) for Female Subjects Walking in Low Heeled Shoes.

5.3.2 Pelvic Rotation Results: Normal Males

The plots and table contained in this section show the rotational results for the tests of male subjects walking barefoot and in shoes. The angular velocity, ω , and the rotation angles, ϕ , θ and β , are shown for each of the three coordinate axes.

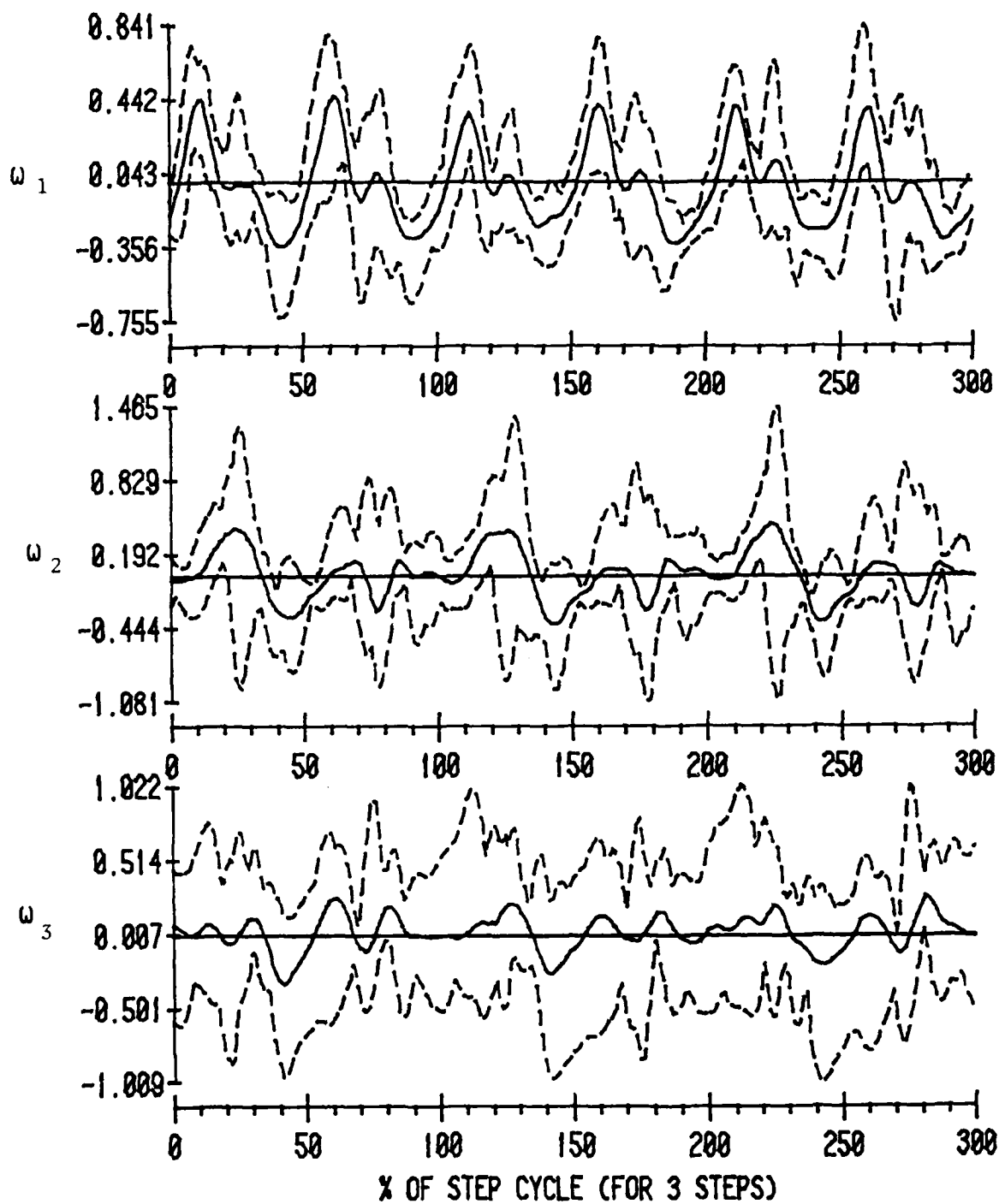


Figure 5-9. Pelvic Angular Velocity (rad/sec) for Male Subjects Walking Barefoot.

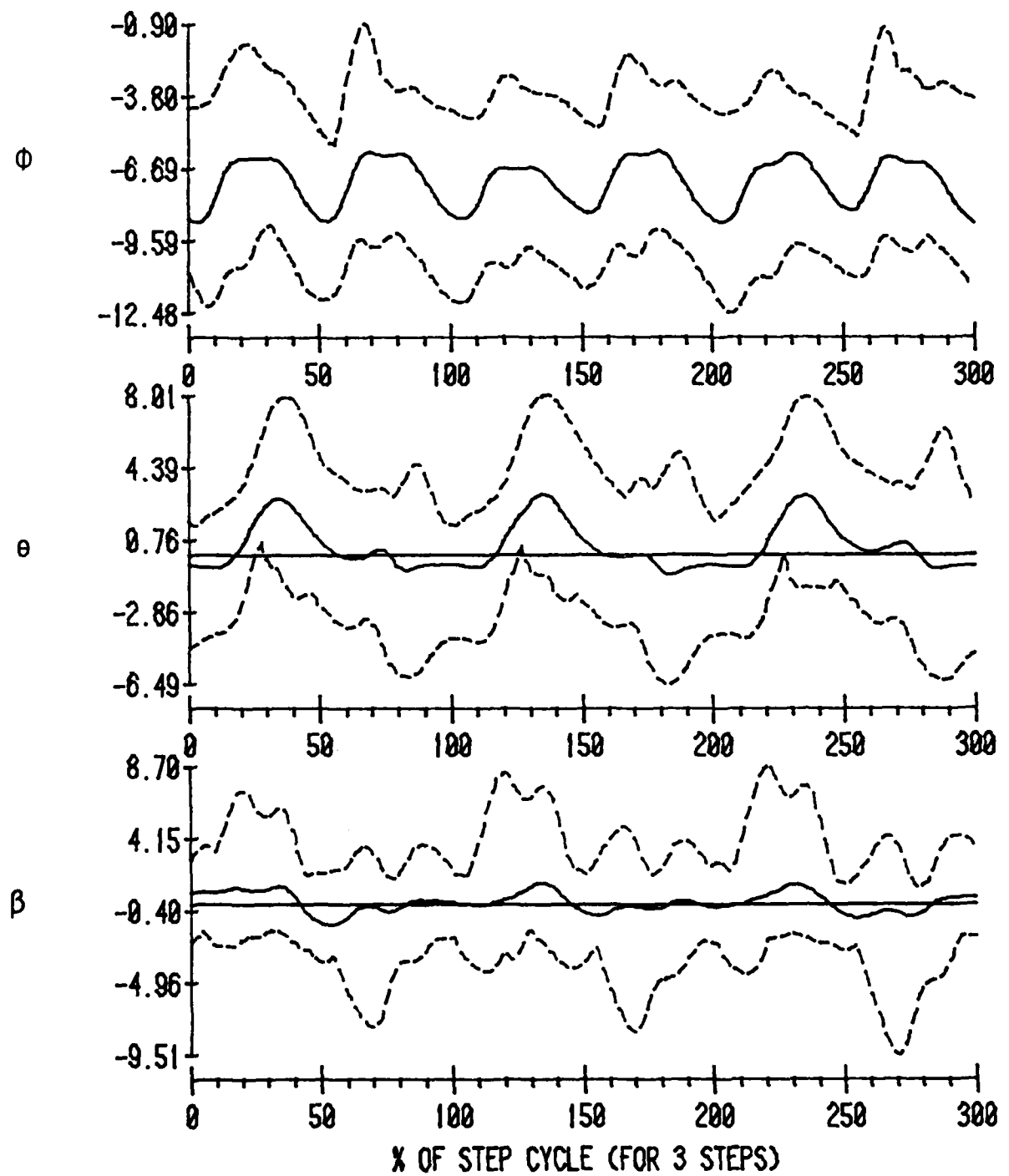


Figure 5-10. Pelvic Rotation Angles (deg) for Male Subjects Walking Barefoot.

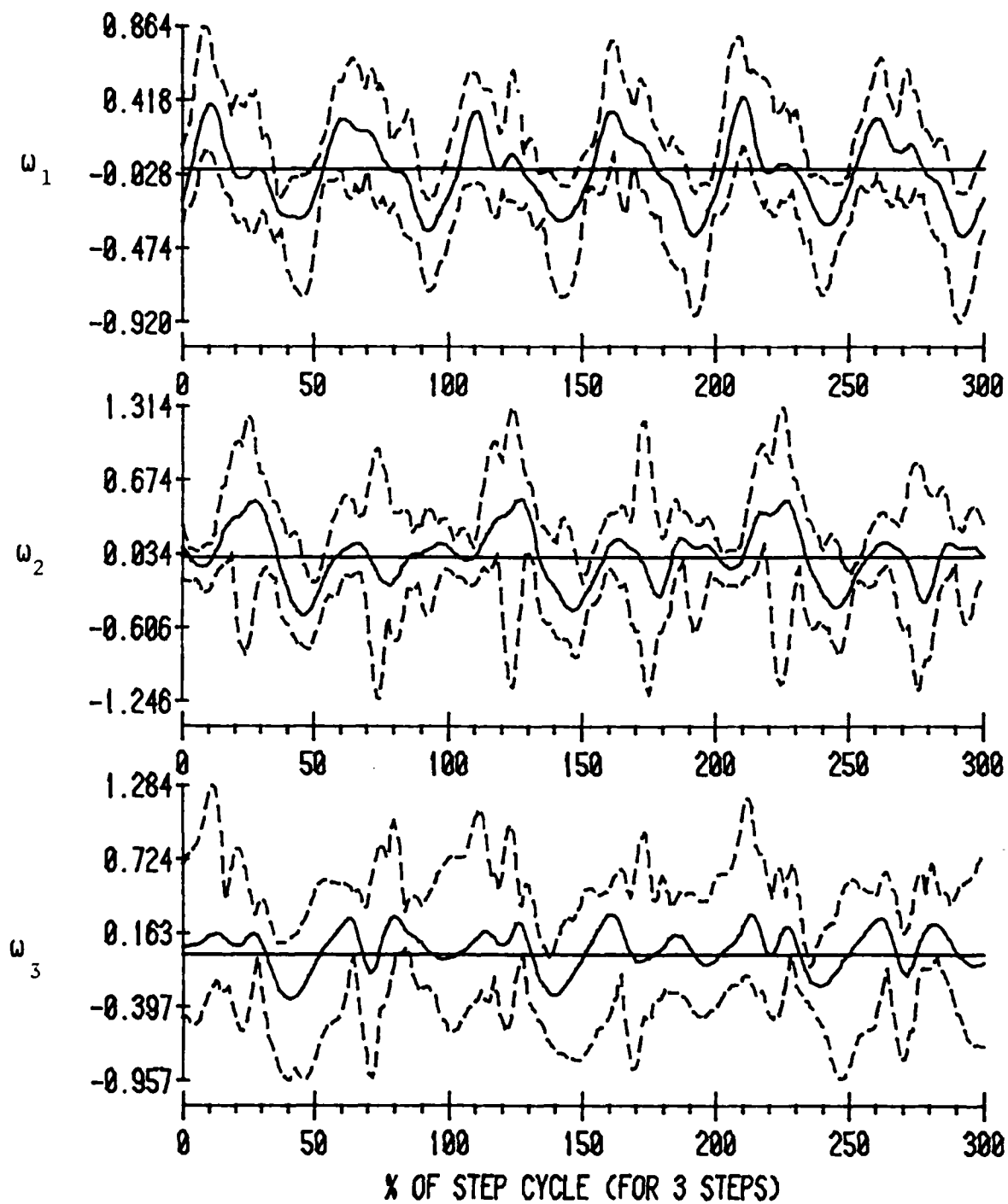


Figure 5-11. Pelvic Angular Velocity (rad/sec) for Male Subjects Walking in Shoes.

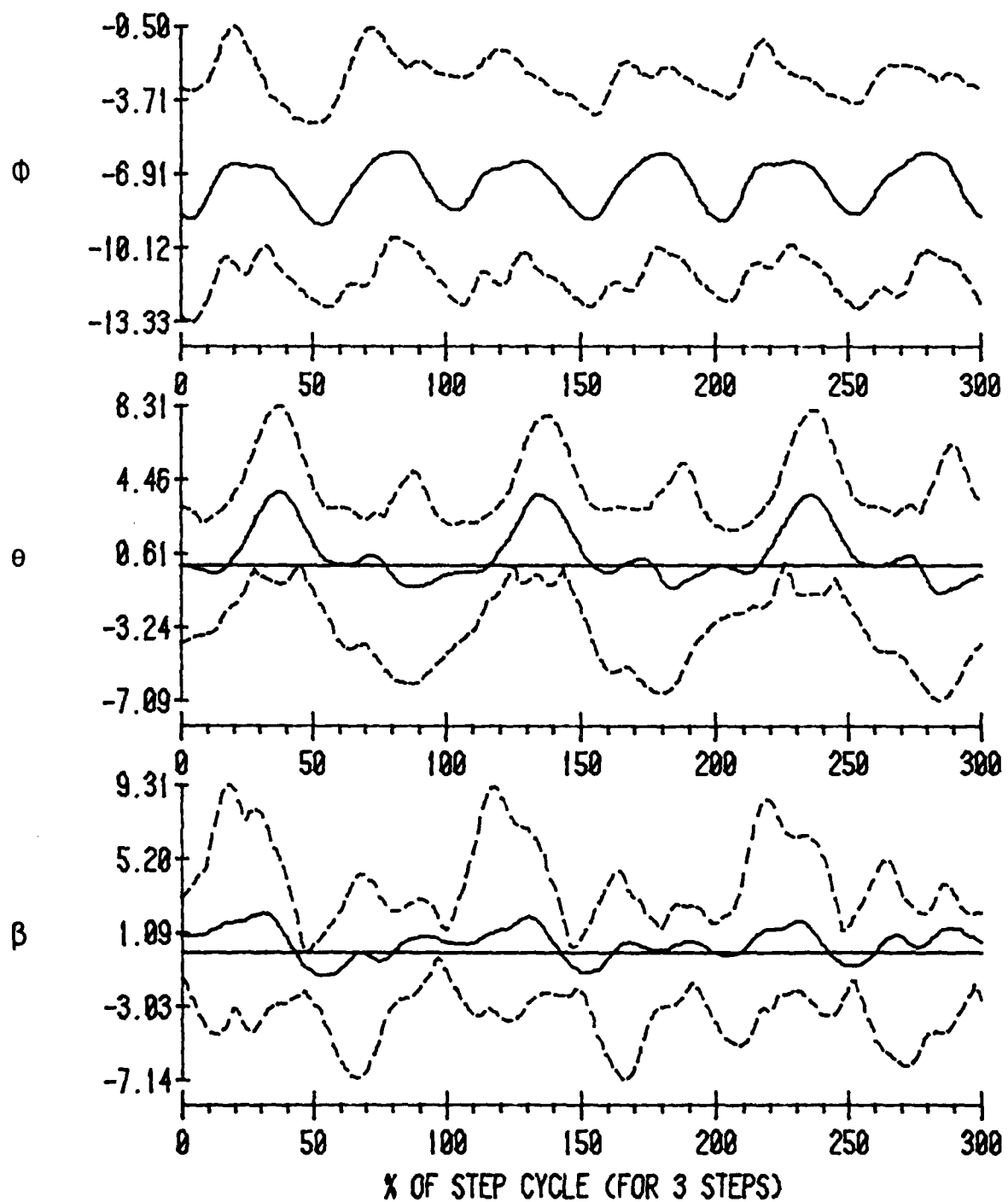


Figure 5-12. Pelvic Rotation Angles (deg) for Male Subjects Walking in Shoes.

| <u>Test 1</u> | | Subject: | 5 | 3 | 2 | 4 | 6 | 7 | 1 | |
|---------------|--|----------------|------|------|--------------------|------|-----------------------------|------|------|-------------|
| | | (Barefoot) | | | | | | | | |
| | | Cadence | 127 | 109 | 100 | 118 | 117 | 110 | 112 | <u>Mean</u> |
| | | $\omega(1)$ | 1.08 | 1.01 | 1.33 | 1.04 | 0.79 | 0.96 | 0.81 | 1.00 |
| | | $\omega(2)$ | 1.65 | 1.78 | 1.14 | 1.12 | 1.43 | 2.05 | 1.25 | 1.49 |
| | | $\omega(3)$ | 1.08 | 1.72 | 0.97 | 0.76 | 1.18 | 1.26 | 0.76 | 1.11 |
| | | θ | 7.4 | 5.7 | 5.5 | 4.6 | 8.7 | 9.5 | 8.9 | 7.2 |
| | | ϕ | 3.6 | 3.9 | 5.3 | 3.7 | 2.7 | 3.4 | 2.6 | 3.6 |
| | | β | 3.7 | 14.8 | 3.9 | 6.6 | 7.0 | 4.5 | 5.3 | 6.6 |
| <u>Test 2</u> | | (Normal Shoes) | | | | | | | | |
| | | Cadence | 121 | 111 | 101 | 115 | 118 | 108 | 106 | <u>Mean</u> |
| | | $\omega(1)$ | 1.62 | 1.04 | 0.99 | 0.67 | 0.96 | 1.16 | 7.78 | 1.03 |
| | | $\omega(2)$ | 1.40 | 1.92 | 0.99 | 1.13 | 1.52 | 2.15 | 1.27 | 1.48 |
| | | $\omega(3)$ | 0.90 | 1.48 | 0.81 | 0.90 | 1.51 | 1.44 | 0.86 | 1.13 |
| | | θ | 6.9 | 6.7 | 4.3 | 4.3 | 9.4 | 10.9 | 8.6 | 7.3 |
| | | ϕ | 4.9 | 3.8 | 3.2 | 2.2 | 2.8 | 4.0 | 2.4 | 3.3 |
| | | β | 2.7 | 14.5 | 4.8 | 6.9 | 6.3 | 4.8 | 7.0 | 6.7 |
| | | | | | ω (Rad/Sec) | | θ, ϕ, β (Deg) | | | |

Table 5-II. Male Subject Peak to Peak Rotational Parameters
Averaged for 3 Step Cycles per Subject.

5.3.3 Pelvic Rotation Results: Normal Females in High Heels

The plots and table contained in this section show the rotational results for the walking test of female subjects wearing high heeled shoes. The angular velocity, ω , and the rotation angles, ϕ , θ and β , are shown for each of the three coordinate axes.

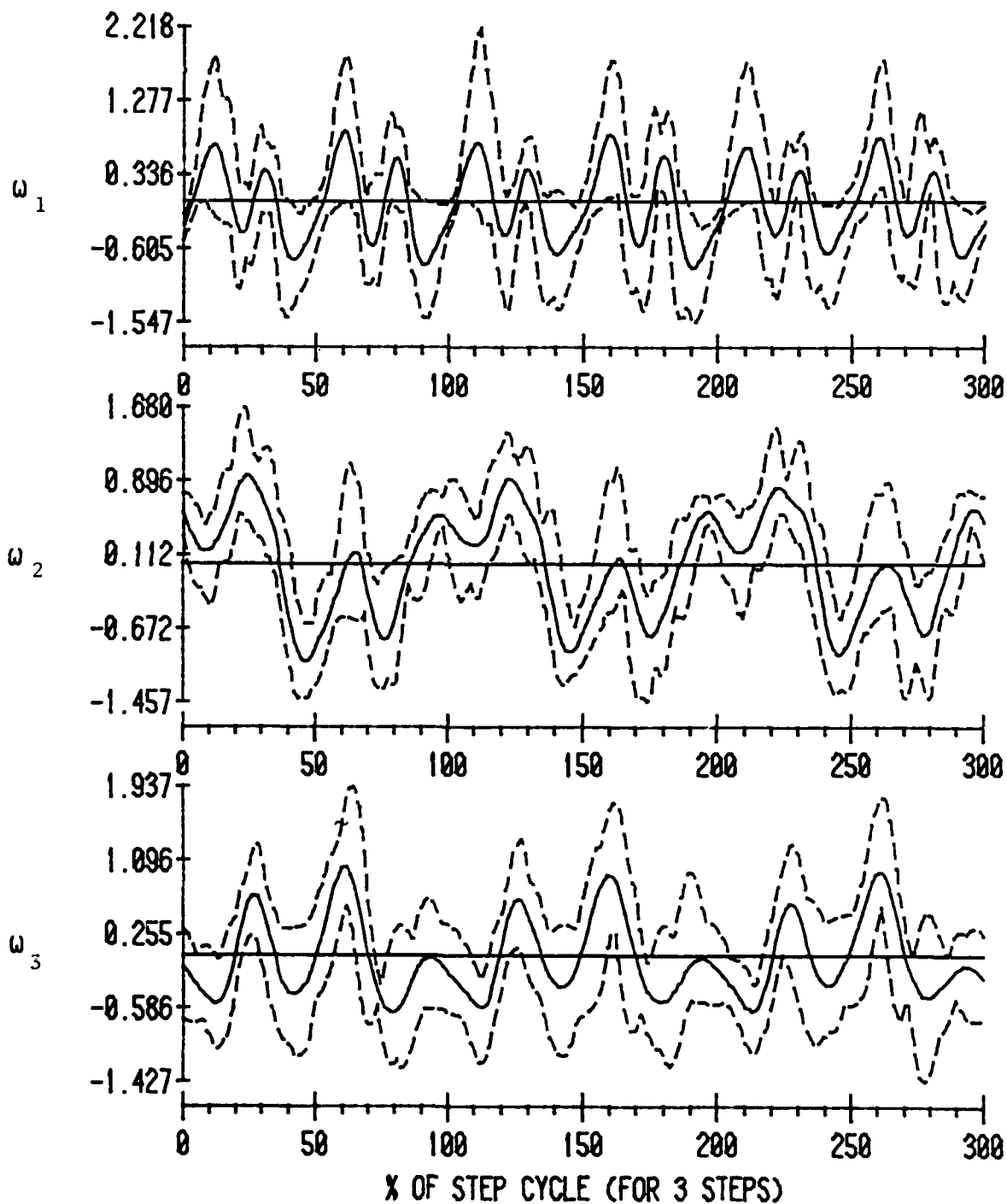


Figure 5-13. Pelvic Angular Velocity (rad/sec) for Female Subjects Walking in High Heeled Shoes.

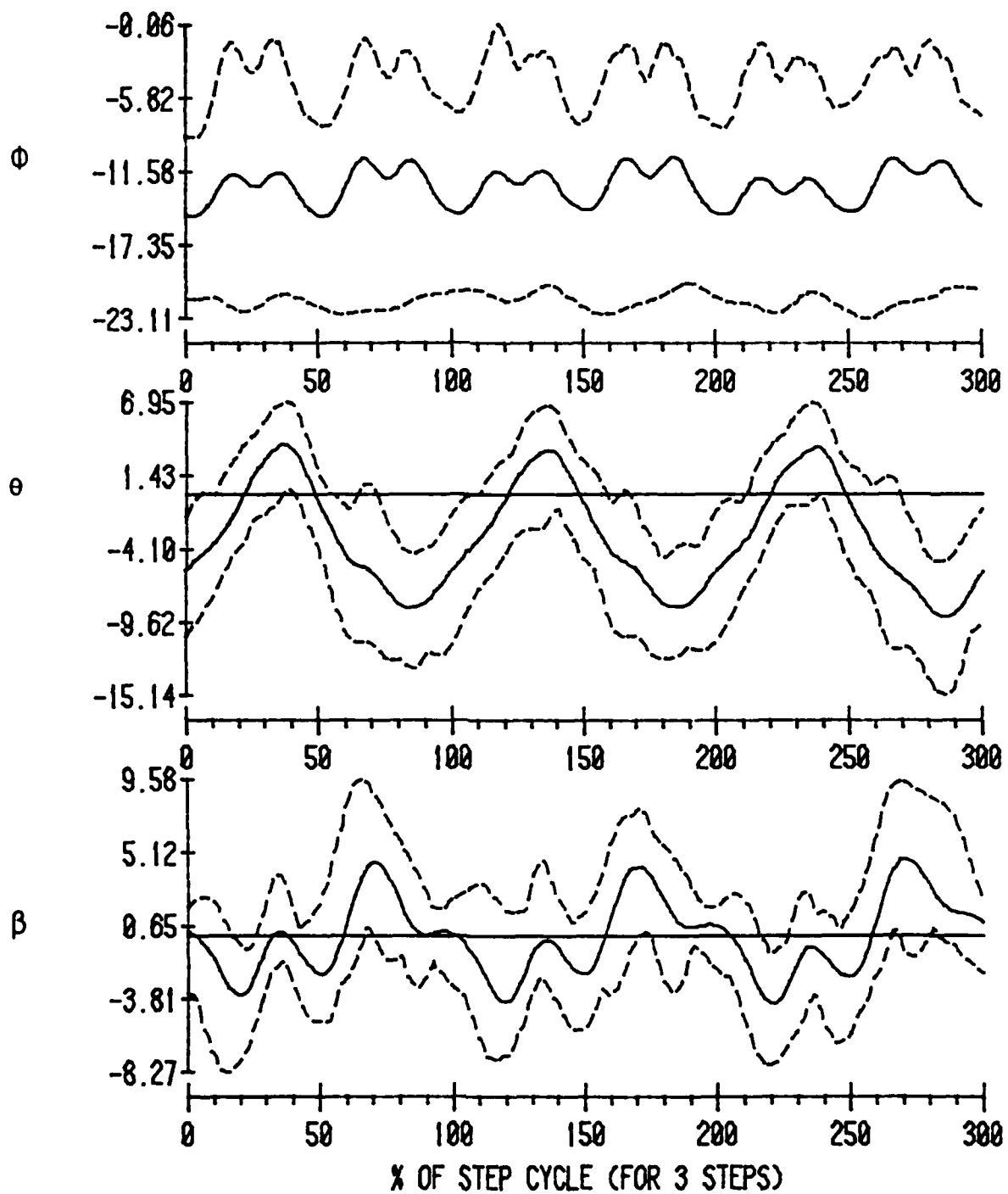


Figure 5-14. Pelvic Rotation Angles (deg) for Female Subjects Walking in High Heeled Shoes.

| Test 4 | Subject: 8 | | 11 | 9 | 12 | 13 | 14 | 10 | Mean |
|--------|---------------------|------|------|------|------|------|------|------|------|
| | (High Heeled Shoes) | | | | | | | | |
| | Cadence | 139 | 131 | 130 | 129 | 141 | 121 | 134 | |
| | $\omega(1)$ | 2.82 | 0.60 | 1.60 | 2.28 | 3.03 | 0.98 | 3.42 | 2.10 |
| | $\omega(2)$ | 2.42 | 1.21 | 1.87 | 2.27 | 2.37 | 1.55 | 2.09 | 1.97 |
| | $\omega(3)$ | 1.90 | 1.26 | 1.14 | 2.02 | 1.64 | 1.24 | 1.76 | 1.57 |
| | θ | 15.0 | 9.9 | 13.0 | 10.4 | 12.3 | 17.6 | 12.9 | 13.0 |
| | ϕ | 7.0 | 1.9 | 5.1 | 5.1 | 6.1 | 3.6 | 8.7 | 5.3 |
| | β | 13.7 | 4.2 | 11.4 | 7.3 | 5.8 | 15.2 | 9.2 | 9.5 |

Cadence (Steps/Min) ω (Rad/Sec) θ, ϕ, β (Deg)

Table 5-III. Female Subject Peak to Peak Rotational Parameters
Averaged for 3 Step Cycles per Subject

5.3.4 Pelvic Rotation Results: Normal Males with Back Load

The plots and table contained in this section show the rotational results for the walking test of male subjects wearing shoes and carrying a 13.6 Kg load on their back. The angular velocity, ω , and rotation angles, ϕ , θ and β , are shown for each of the three coordinate axes.

5.4 Translational Results

The following sections contain the experimental results of the acceleration, velocity and position of the pelvis measured in this study. A brief description of the walking test precedes the graphical results presented in each of the following sections.

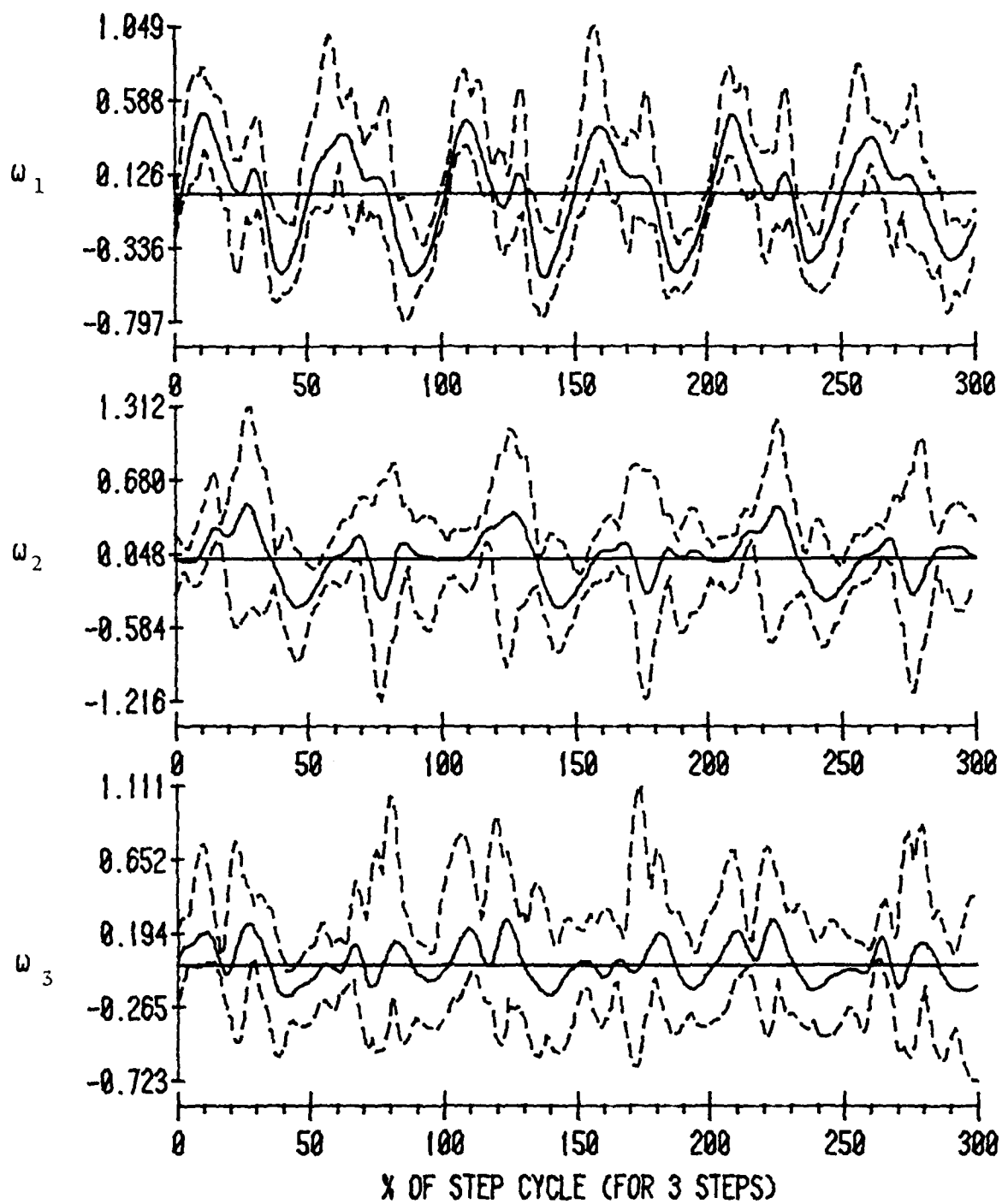


Figure 5-15. Pelvic Angular Velocity (rad/sec) for Male Subjects Walking in Shoes with a Back Load.

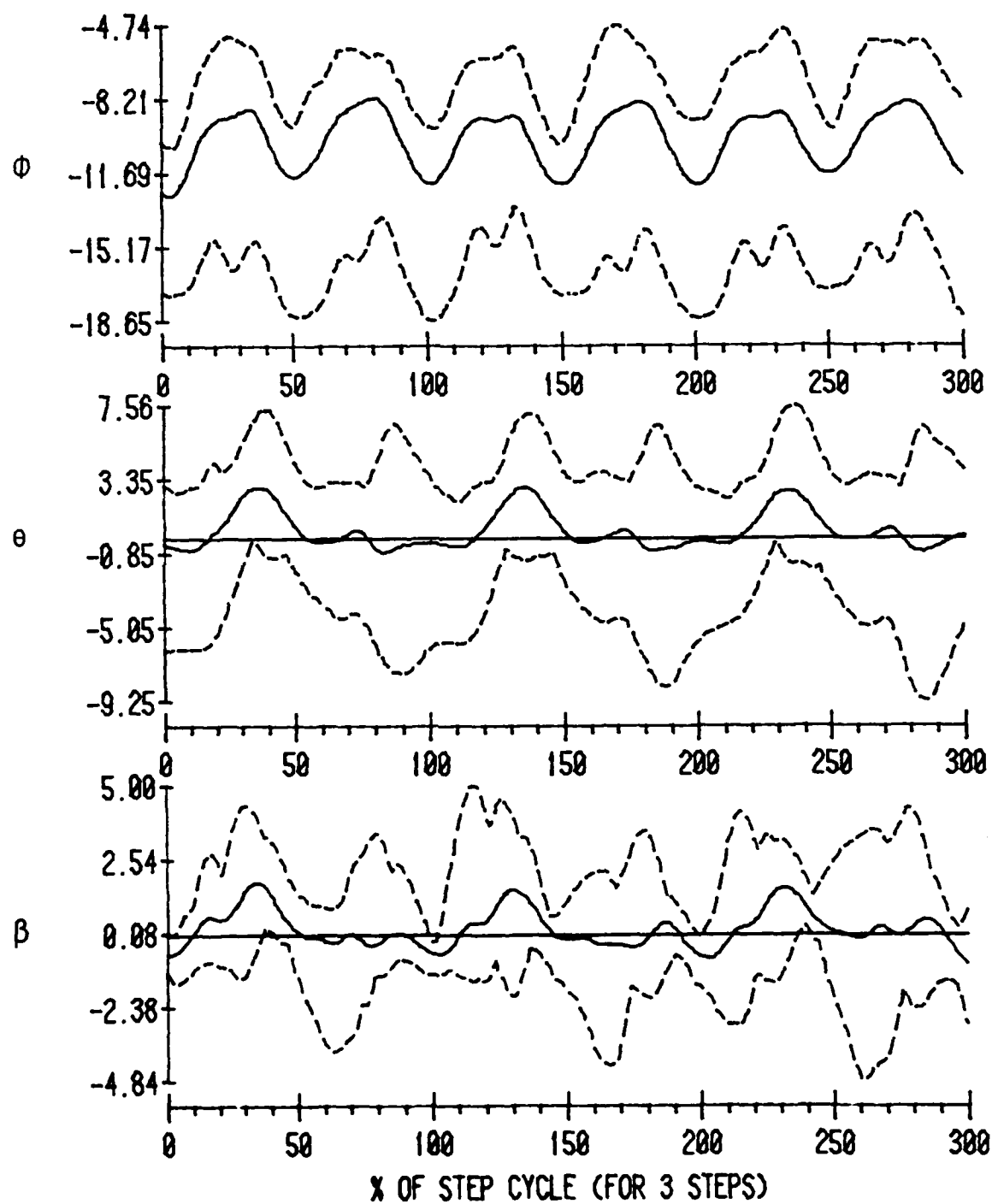


Figure 5-16. Pelvic Rotation Angles (deg) for Male Subjects Walking in Shoes with a Back Load.

| Subject: 5 | | 3 | 2 | 4 | 6 | 7 | 1 | <u>Mean</u> |
|------------------------|------|---------------------|------|--------------------|------|-----------------------------|------|-------------|
| Test 3 (Carrying Load) | | | | | | | | |
| Cadence | 118 | 110 | 98 | 115 | 114 | 110 | 105 | 105 |
| $\omega(1)$ | 1.37 | 1.15 | 1.11 | 1.63 | 1.35 | 1.01 | .79 | 1.20 |
| $\omega(2)$ | 1.26 | 1.40 | 1.14 | 1.32 | 1.51 | 2.14 | 1.30 | 1.44 |
| $\omega(3)$ | 0.70 | 1.10 | 0.70 | 1.03 | 1.04 | 1.23 | 0.70 | 0.93 |
| θ | 5.2 | 7.6 | 6.0 | 5.0 | 9.3 | 9.6 | 8.0 | 7.2 |
| ϕ | 4.5 | 3.8 | 5.2 | 5.8 | 3.9 | 3.5 | 3.5 | 4.3 |
| β | 3.1 | 7.9 | 5.0 | 4.6 | 3.2 | 3.8 | 2.4 | 4.3 |
| | | Cadence (Steps/Min) | | ω (Rad/Sec) | | θ, ϕ, β (Deg) | | |

Table 5-IV. Male Subject Peak to Peak Rotational Parameters
Averaged for 3 Step Cycles per Subject.

5.4.1 Pelvic Translation Results: Normal Females

The plots and table contained in this section show the translation results for tests of female subjects walking barefoot and in low heeled shoes. The acceleration, ACC, velocity, VEL, and position, POS, of the pelvis are shown for each of the three coordinate axes.

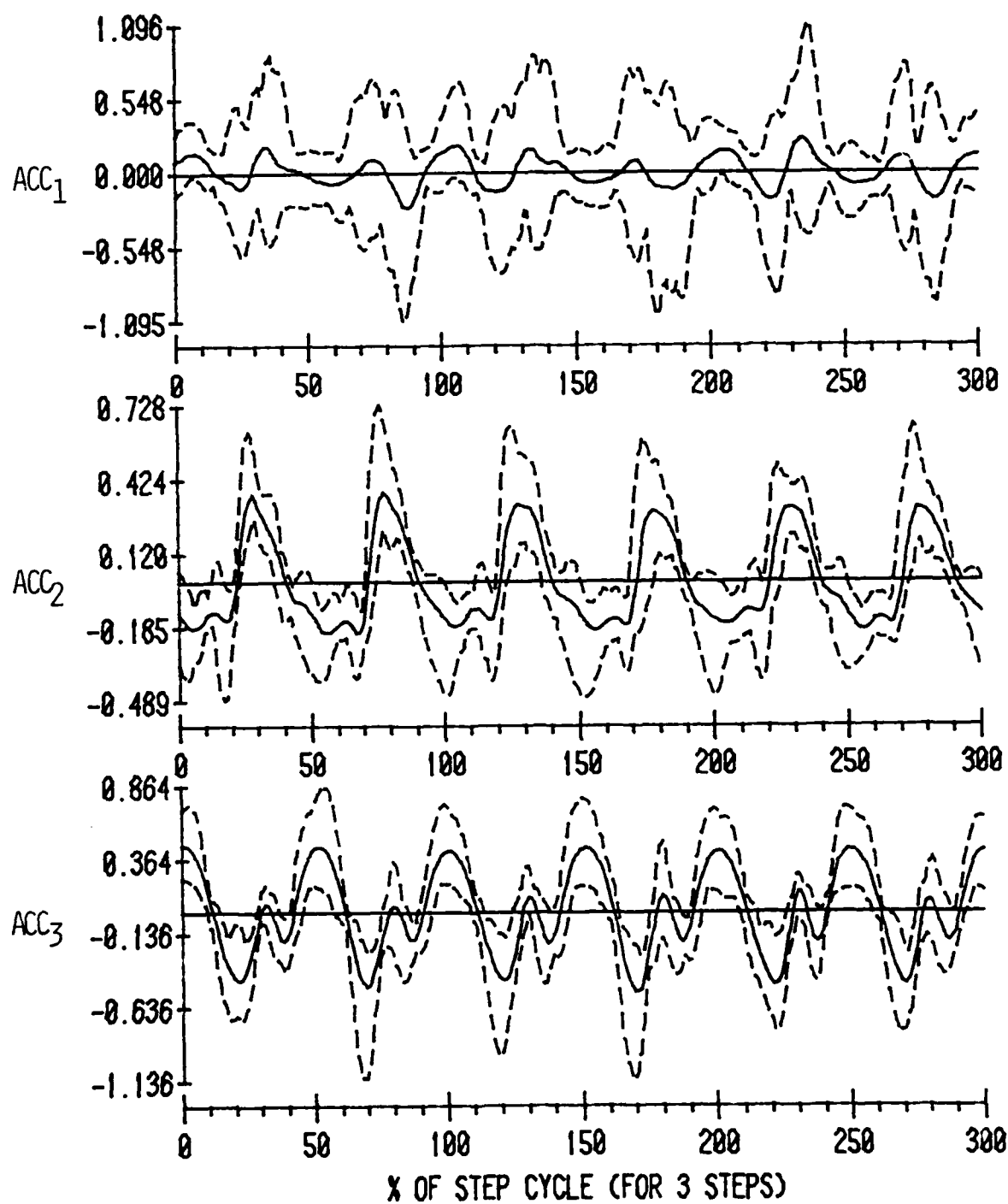


Figure 5-17. Pelvic Acceleration (g's) for Female Subjects Walking Barefoot.

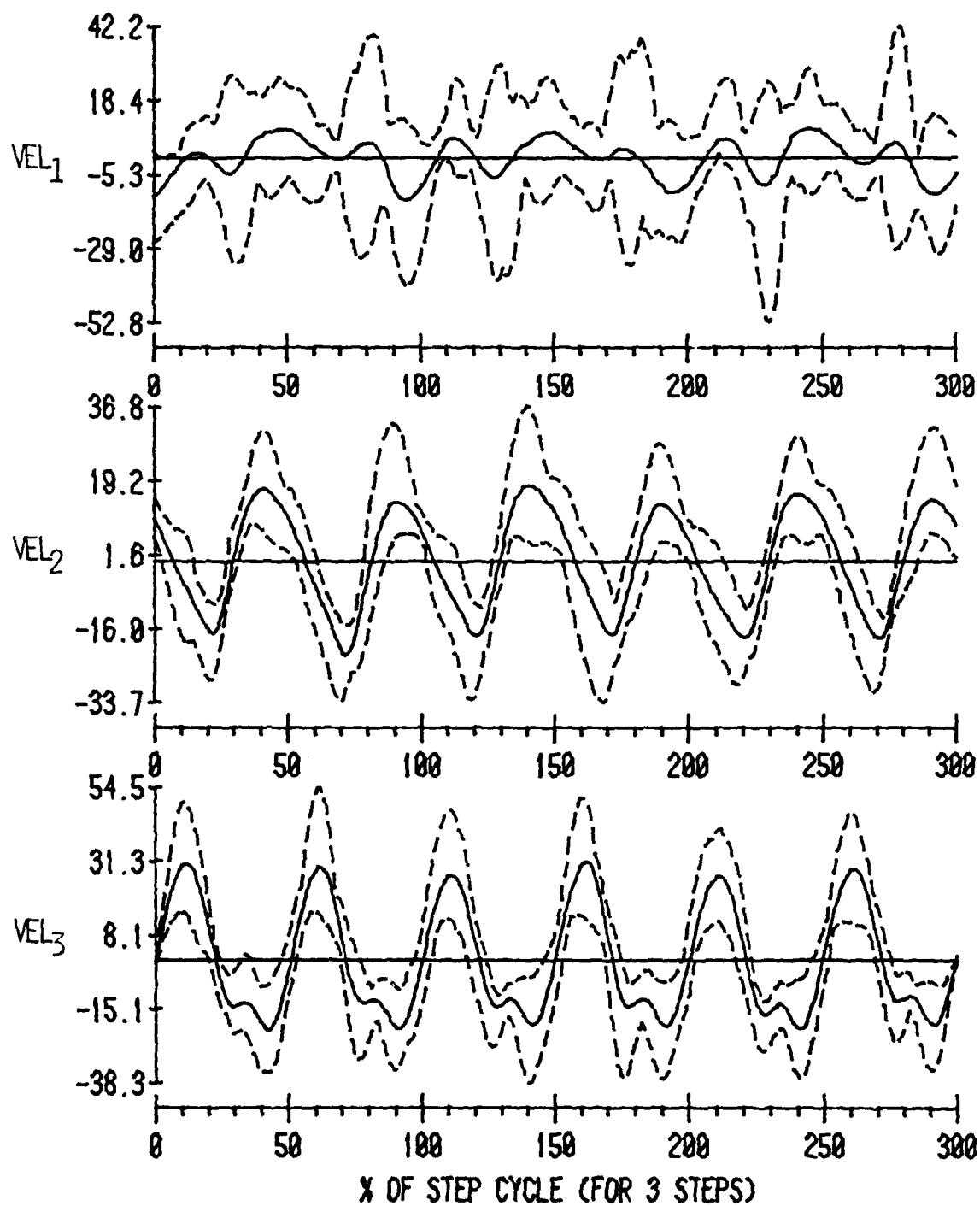


Figure 5-18. Pelvic Velocity (cm/sec) for Female Subjects Walking Barefoot.

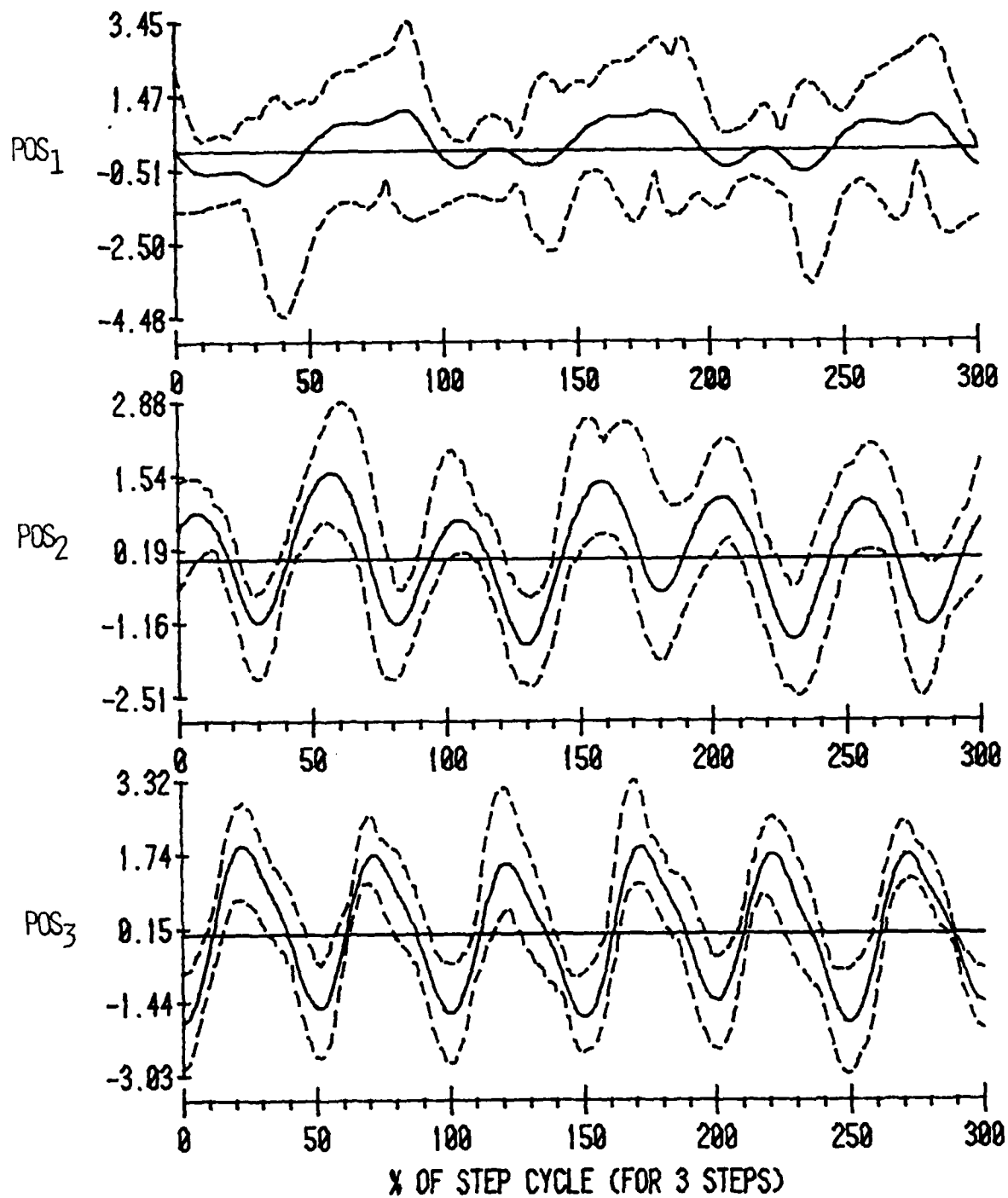


Figure 5-19. Pelvic Position (cm) for Female Subjects Walking Barefoot.

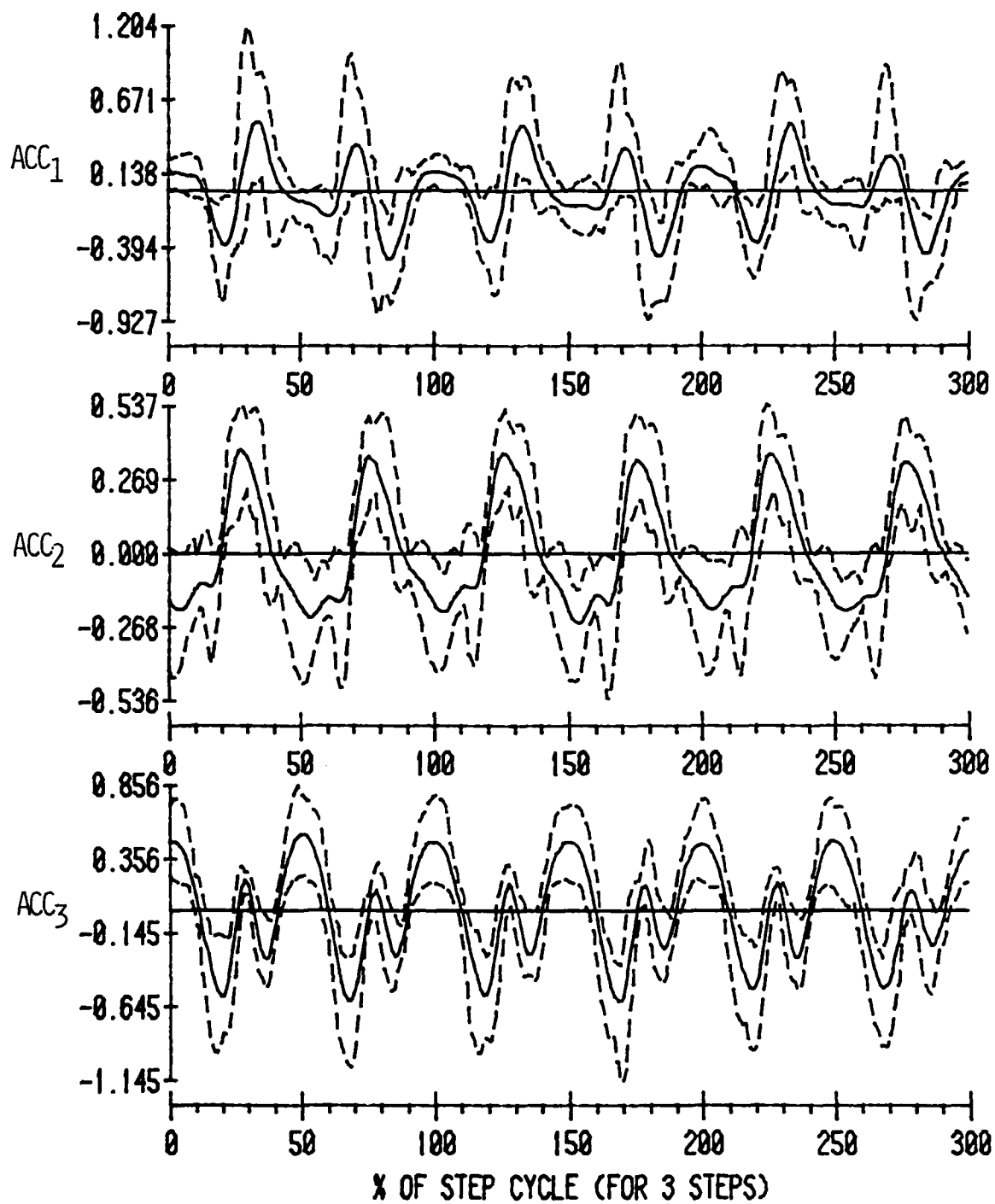


Figure 5-20. Pelvic Acceleration (g's) for Female Subjects Walking in Low Heeled Shoes.

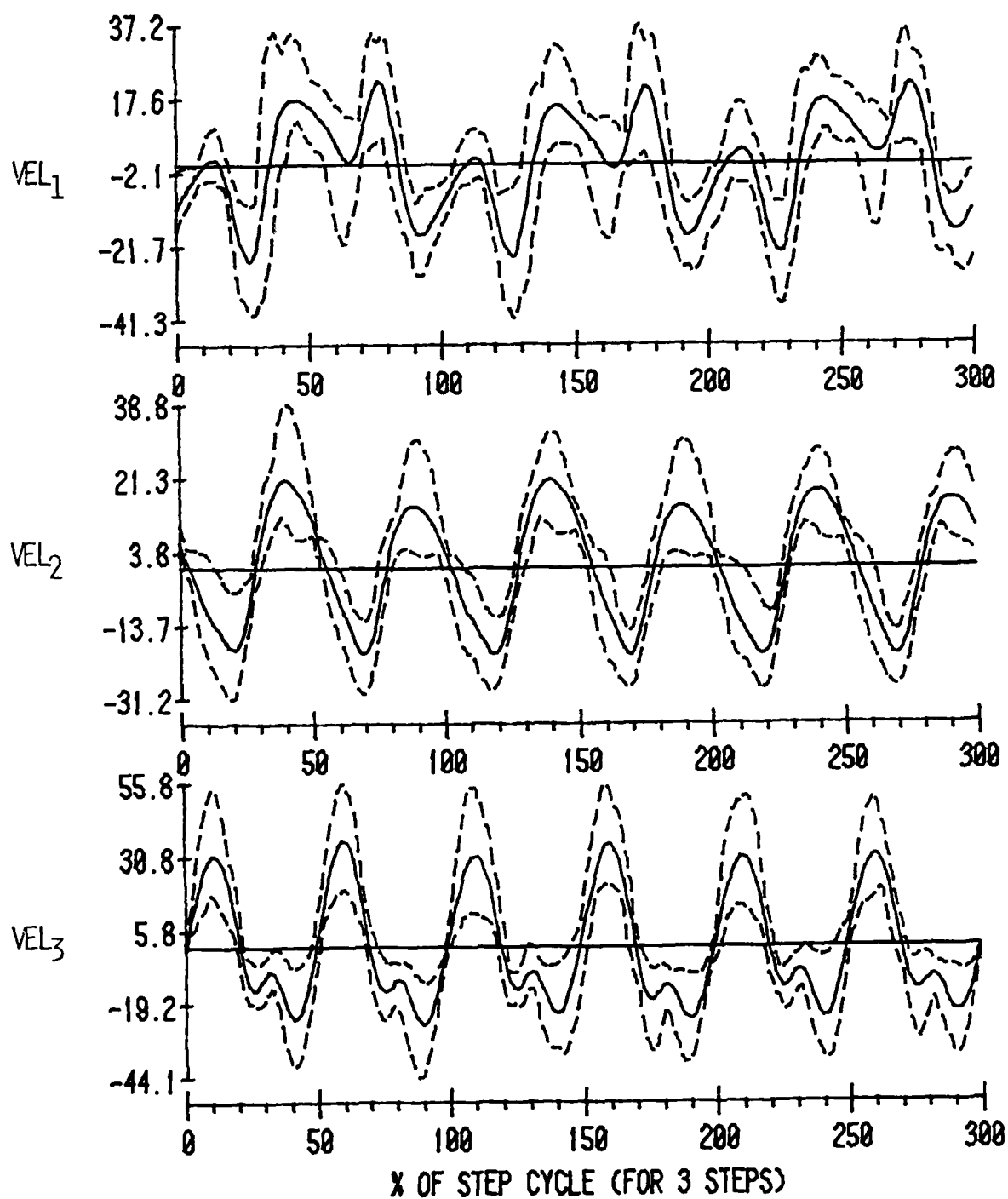


Figure 5-21. Pelvic Velocity (cm/sec) for Female Subjects Walking in Low Heeled Shoes.

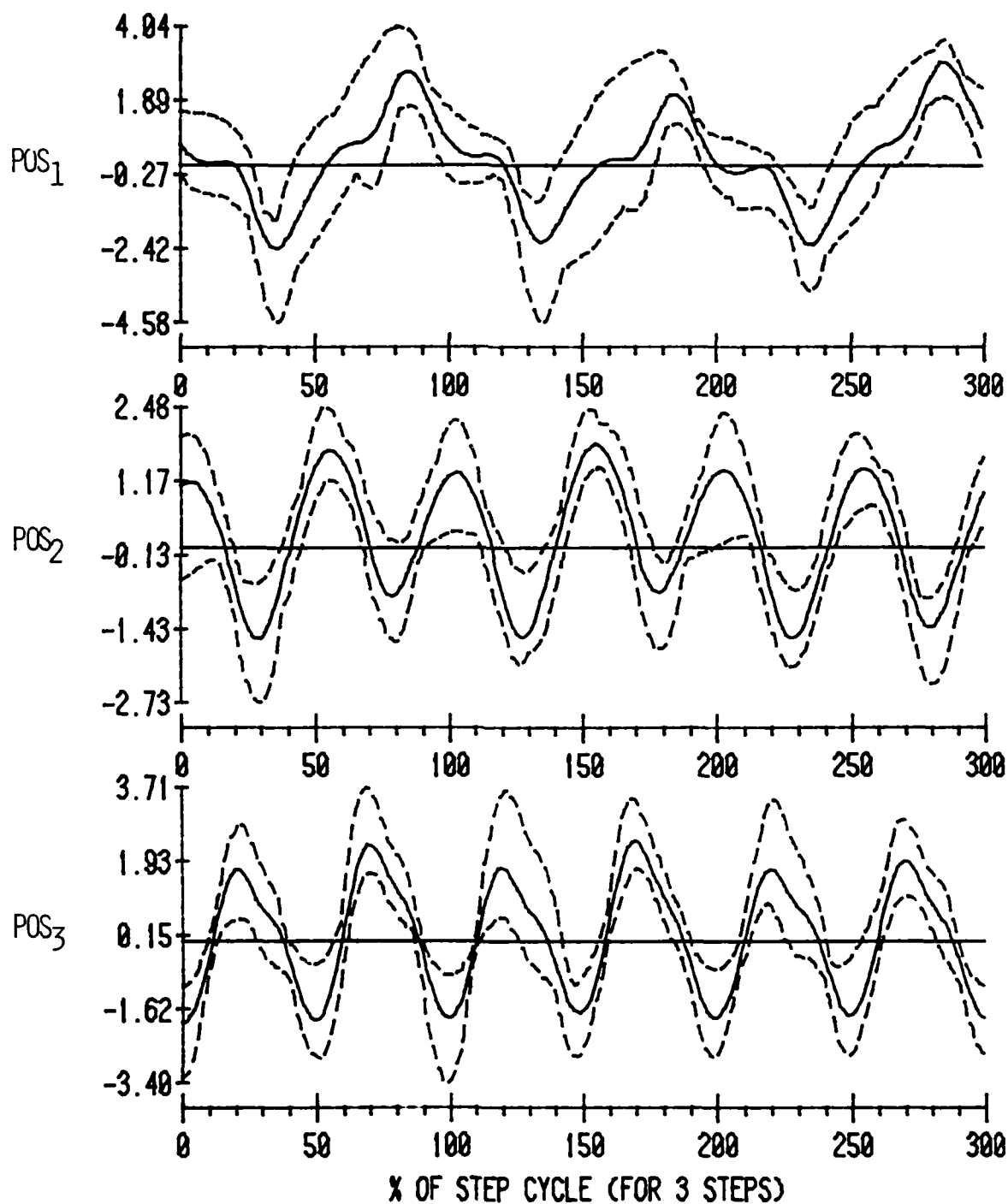


Figure 5-22. Pelvic Position (cm) for Female Subjects Walking in Low Heeled Shoes.

| Test 1 | Subject: 8 | | 11 | 9 | 12 | 13 | 14 | 10 | Mean |
|---------------------------|------------|------|---------------------|-----------|--------------|----------|------|------|------|
| | (Barefoot) | | | | | | | | |
| | Cadence | 142 | 131 | 124 | 136 | 142 | 121 | 137 | |
| | ACC(1) | .77 | 0.84 | 0.43 | 1.74 | 1.51 | 0.89 | 1.30 | 1.21 |
| | ACC(2) | 1.04 | 0.63 | 0.49 | 0.62 | 0.47 | 0.46 | 0.86 | 0.65 |
| | ACC(3) | 1.75 | 0.47 | 0.66 | 0.99 | 1.39 | 0.73 | 1.35 | 1.05 |
| | VEL(1) | 68.7 | 40.9 | 30.3 | 75.9 | 48.6 | 49.6 | 60.9 | 53.5 |
| | VEL(2) | 62.8 | 32.2 | 34.1 | 41.0 | 22.6 | 33.5 | 38.9 | 37.9 |
| | VEL(3) | 81.0 | 27.2 | 38.5 | 50.0 | 66.4 | 37.2 | 74.5 | 53.5 |
| | POS(1) | 4.7 | 4.3 | 2.9 | 7.0 | 3.0 | 3.3 | 3.2 | 4.0 |
| | POS(2) | 4.0 | 2.4 | 3.4 | 2.7 | 1.4 | 2.8 | 2.3 | 2.7 |
| | POS(3) | 5.4 | 2.0 | 3.2 | 3.6 | 4.5 | 2.8 | 5.1 | 3.8 |
| Test 2 (Low Heeled Shoes) | | | | | | | | | |
| | Cadence | 134 | 129 | 128 | 126 | 142 | 124 | 132 | Mean |
| | ACC(1) | 1.50 | 0.63 | 0.59 | 1.66 | 1.97 | 1.04 | 1.12 | 1.22 |
| | ACC(2) | 0.94 | 0.69 | 0.52 | 0.68 | 0.46 | 0.60 | 0.97 | 0.70 |
| | ACC(3) | 1.70 | 0.57 | 0.82 | 1.16 | 1.37 | 0.88 | 1.64 | 1.17 |
| | VEL(1) | 69.3 | 47.7 | 33.3 | 73.5 | 68.3 | 62.3 | 50.1 | 57.8 |
| | VEL(2) | 61.4 | 36.4 | 33.9 | 46.4 | 22.2 | 41.7 | 44.2 | 40.9 |
| | VEL(3) | 82.6 | 30.1 | 48.0 | 6.01 | 67.0 | 43.5 | 91.2 | 60.4 |
| | POS(1) | 5.0 | 5.6 | 3.0 | 7.7 | 4.6 | 5.8 | 4.4 | 5.2 |
| | POS(2) | 4.3 | 3.0 | 2.6 | 3.4 | 1.3 | 2.9 | 2.5 | 2.9 |
| | POS(3) | 5.5 | 2.5 | 3.2 | 4.2 | 4.3 | 3.7 | 6.3 | 4.3 |
| | | | Cadence (Steps/Min) | ACC (g's) | VEL (Cm/Sec) | POS (Cm) | | | |

Table 5-V. Female Subject Peak to Peak Translational Parameters
Averaged for 3 Step Cycles per Subject

5.4.2 Pelvic Translation Results: Normal Males

The plots and table contained in this section show the translation results for tests of male subjects walking barefoot and in shoes. The acceleration, ACC, velocity, VEL, and position, POS, of the pelvis are shown for each of the three coordinate axes.

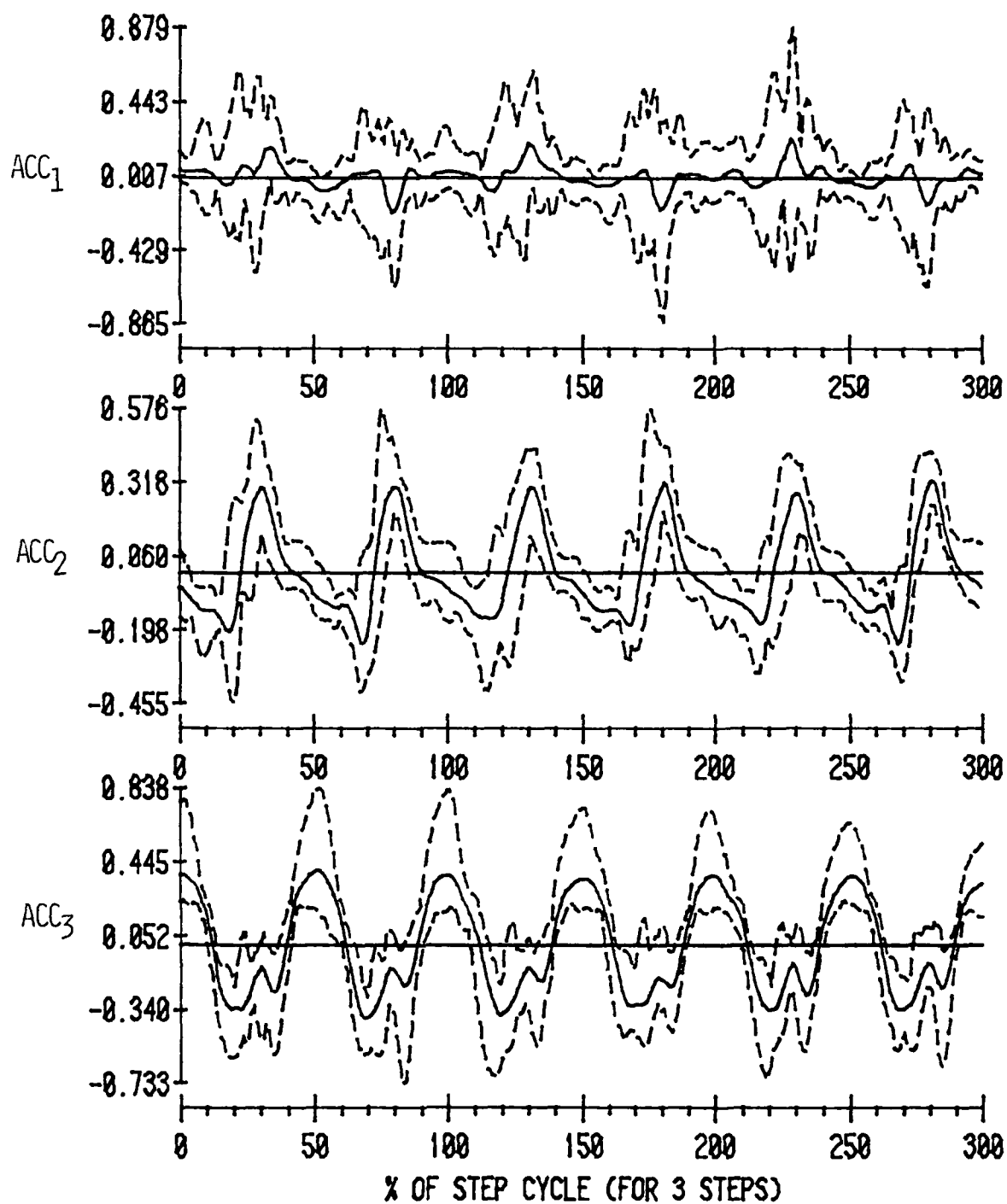


Figure 5-23. Pelvic Acceleration (g's) for Male Subjects Walking Barefoot.

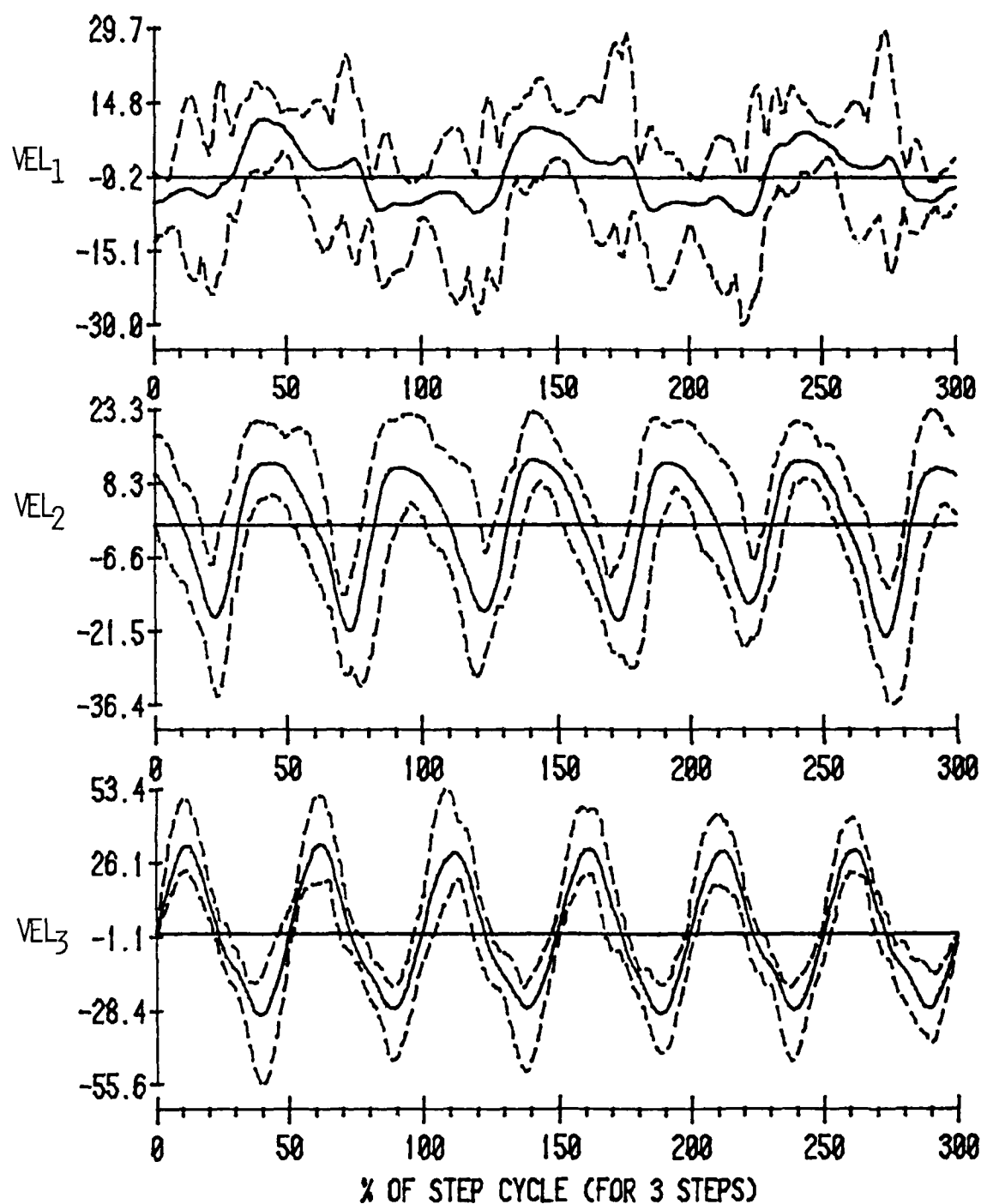


Figure 5-24. Pelvic Velocity (cm/sec) for Male Subjects Walking Barefoot.

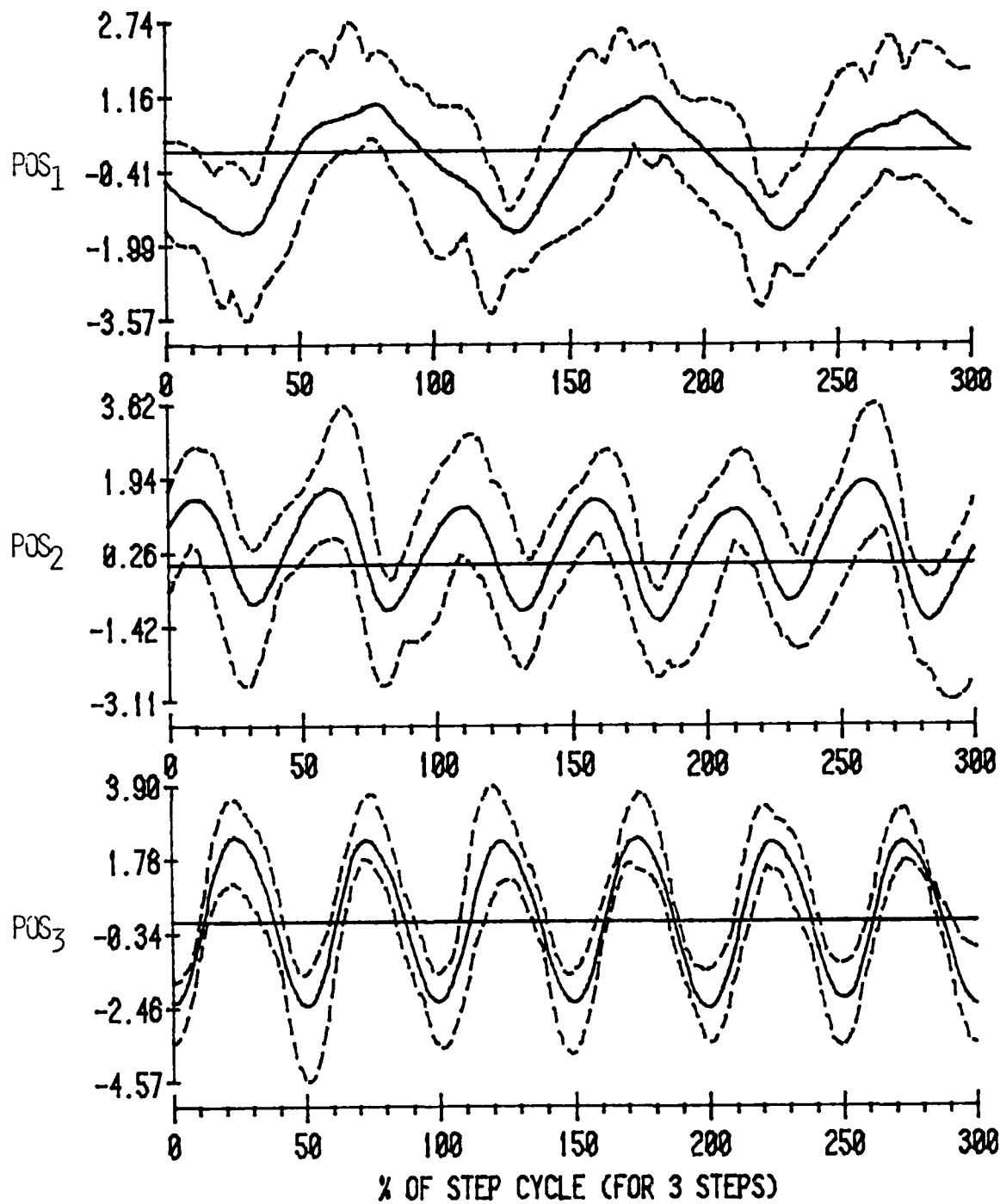


Figure 5-25. Pelvic Position (cm) for Male Subjects Walking Barefoot.

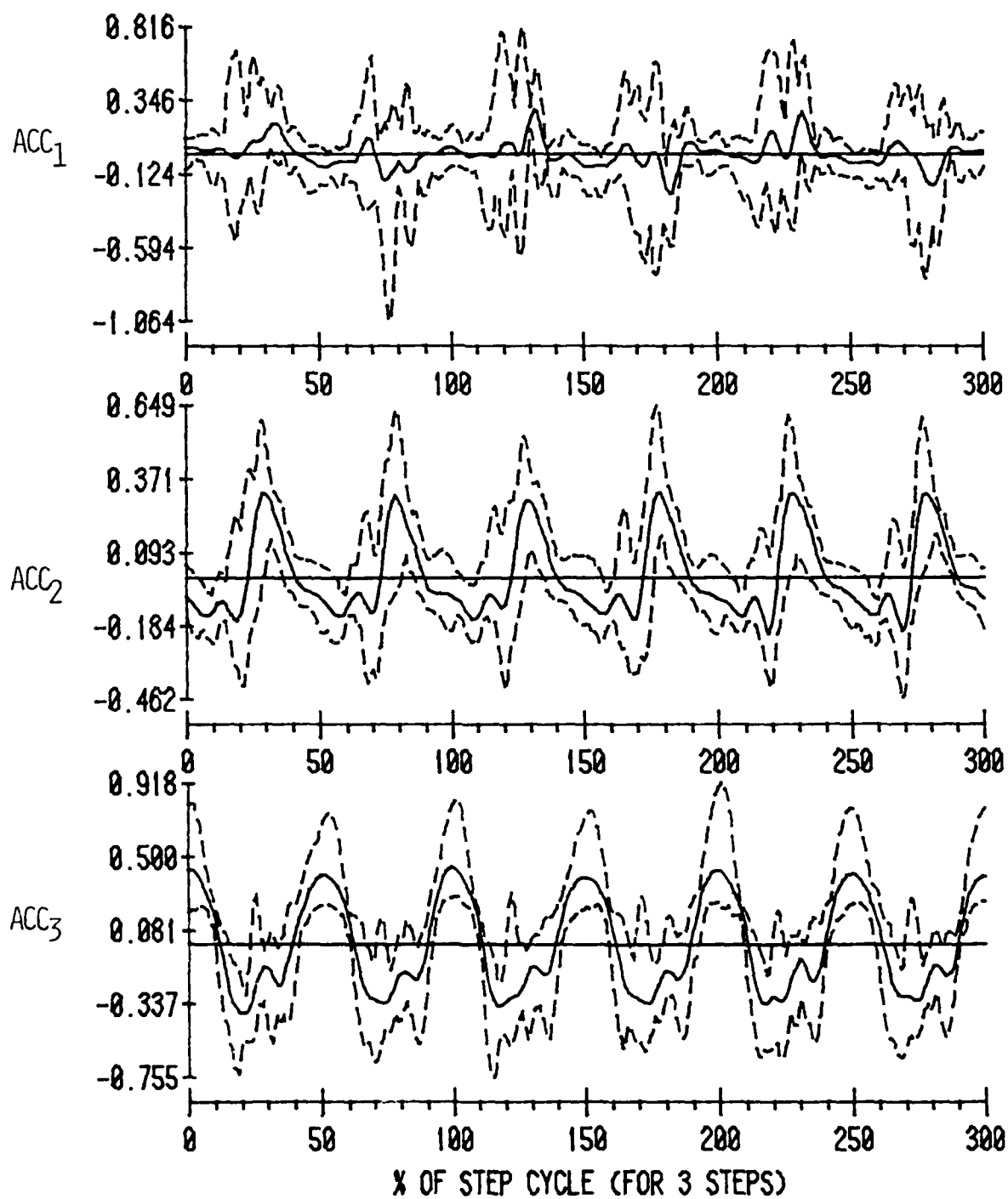


Figure 5-26. Pelvic Acceleration (g's) for Male Subjects Walking in Shoes.

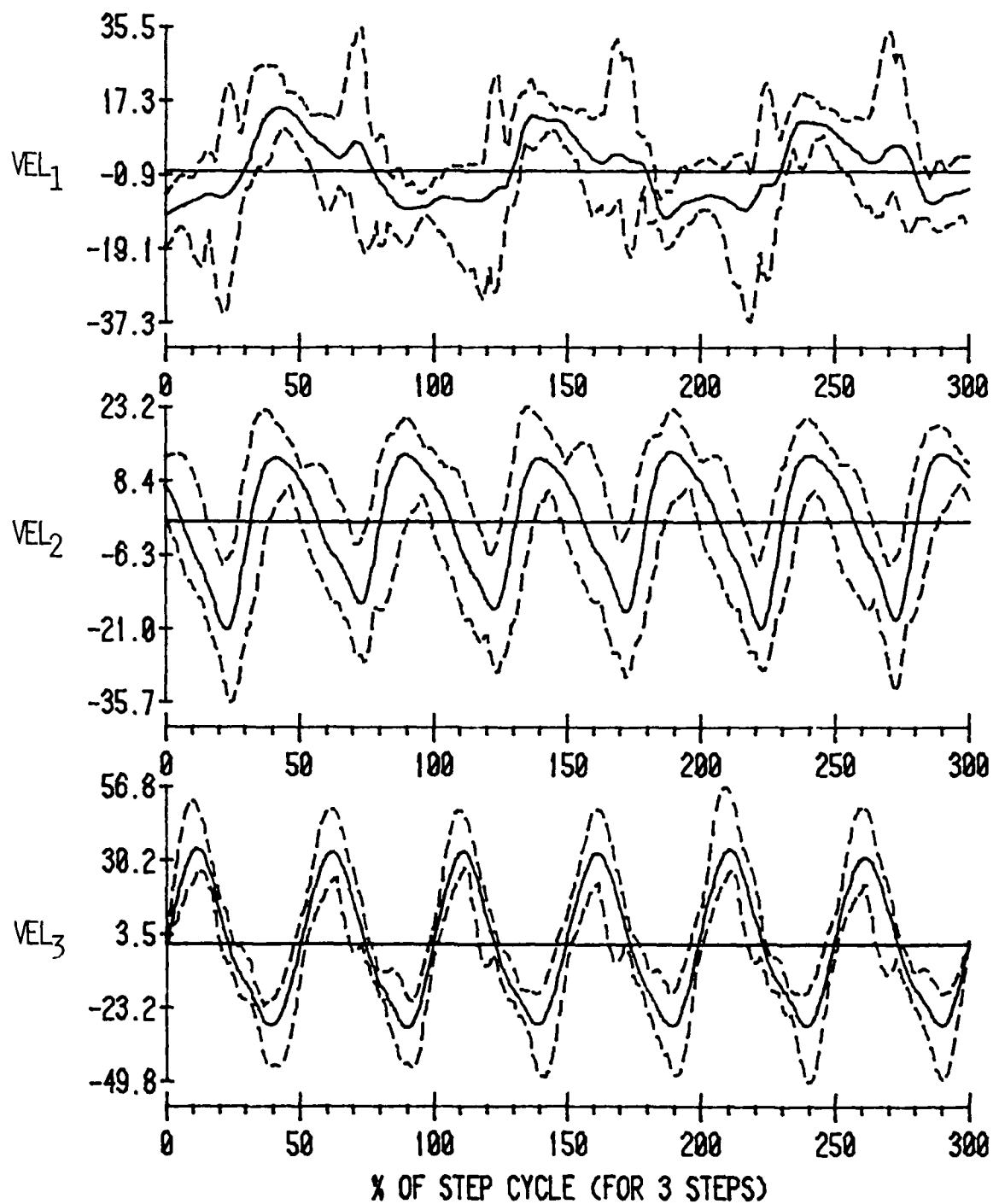


Figure 5-27. Pelvic Velocity (cm/sec) for Male Subjects
Walking in Shoes.

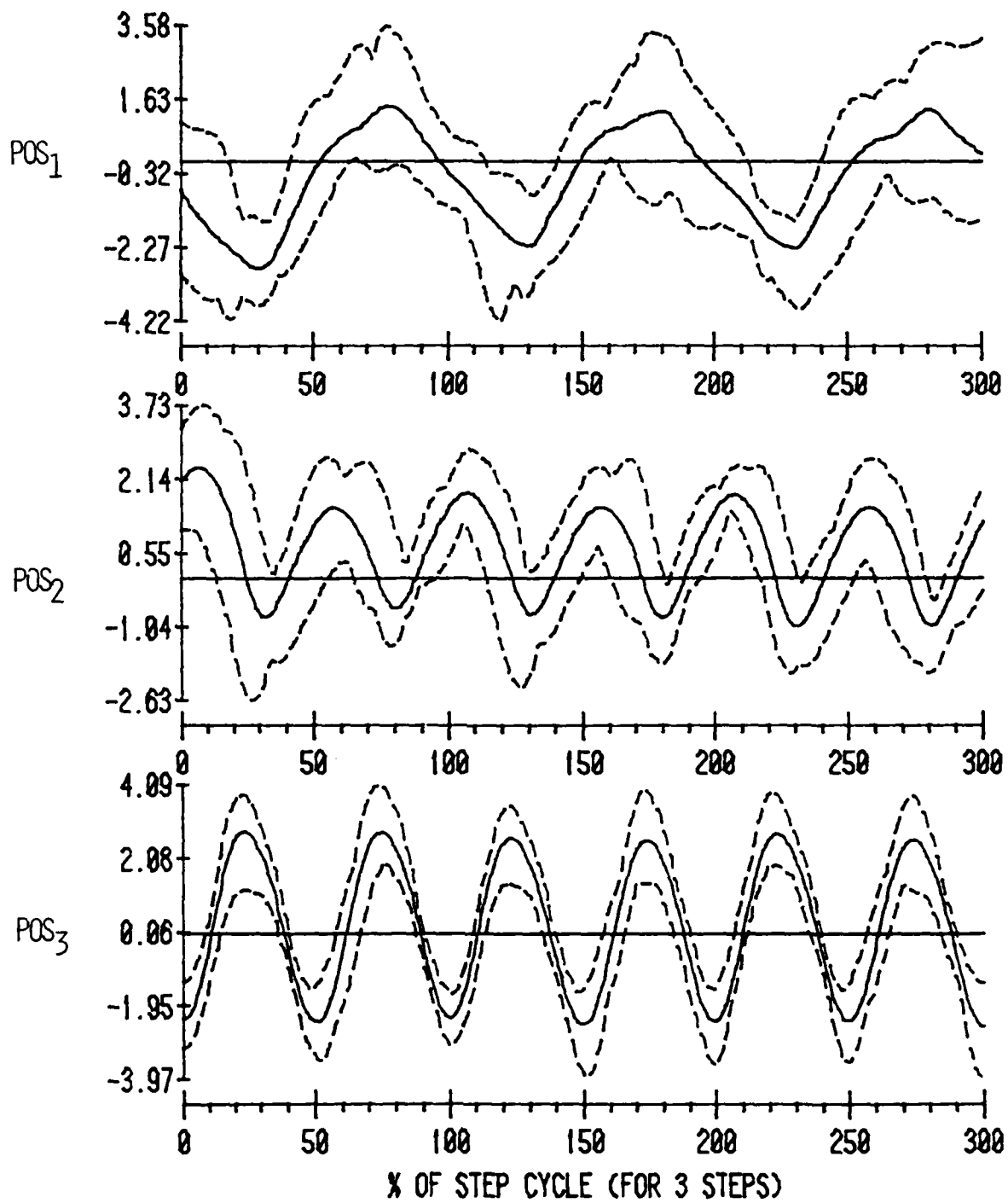


Figure 5-28. Pelvic Position (cm) for Male Subjects Walking in Shoes.

| Test 1 | Subject: | 5 | 3 | 2 | 4 | 6 | 7 | 1 | Mean |
|----------------------|-----------|------|---------------------|-----------|--------------|----------|------|------|------|
| | | | | | | | | | |
| Test 1 (Barefoot) | Cadence | 127 | 109 | 100 | 118 | 117 | 110 | 112 | |
| | ACC(1) | 0.87 | 1.20 | 0.56 | 0.69 | 0.97 | 1.31 | 0.72 | 0.90 |
| | ACC(2) | 0.90 | 0.71 | 0.60 | 0.60 | 0.47 | 0.62 | 0.54 | 0.63 |
| | ACC(3) | 1.40 | 0.75 | 0.64 | 1.11 | 0.81 | 0.61 | 0.75 | 0.87 |
| | VEL(1) | 38.3 | 44.3 | 24.1 | 31.6 | 54.6 | 47.0 | 23.5 | 37.6 |
| | VEL(2) | 48.6 | 42.6 | 46.6 | 35.8 | 30.5 | 35.7 | 33.4 | 39.2 |
| | VEL(3) | 97.0 | 56.1 | 54.8 | 80.2 | 52.9 | 46.6 | 46.0 | 61.9 |
| | POS(1) | 3.4 | 5.9 | 2.2 | 3.6 | 4.2 | 4.6 | 2.6 | 3.8 |
| | POS(2) | 3.1 | 4.1 | 3.6 | 3.1 | 2.3 | 3.4 | 2.6 | 3.2 |
| | POS(3) | 7.1 | 5.0 | 5.0 | 6.6 | 3.6 | 4.4 | 4.1 | 5.1 |
| Test 2 (Shoes) | | | | | | | | | |
| Test 2 (Shoes) | Cadence | 121 | 111 | 101 | 115 | 118 | 108 | 106 | Mean |
| | ACC(1) | 1.07 | 1.17 | 0.55 | 0.67 | 1.24 | 1.58 | 0.61 | 0.99 |
| | ACC(2) | 1.01 | 0.67 | 0.50 | 0.73 | 0.52 | 0.63 | 0.53 | 0.66 |
| | ACC(3) | 1.42 | 0.96 | 0.60 | 1.09 | 1.05 | 0.70 | 0.75 | 0.94 |
| | VEL(1) | 38.1 | 47.4 | 27.1 | 32.2 | 68.5 | 59.8 | 24.8 | 42.6 |
| | VEL(2) | 49.0 | 39.4 | 35.2 | 41.6 | 32.8 | 43.2 | 42.8 | 40.6 |
| | VEL(3) | 96.8 | 66.5 | 49.0 | 81.4 | 62.3 | 58.3 | 52.1 | 66.6 |
| | POS(1)4.1 | | 6.6 | 3.1 | 4.1 | 6.3 | 6.0 | 3.4 | 4.8 |
| | POS(2) | 3.3 | 3.2 | 2.8 | 2.9 | 2.7 | 3.7 | 2.8 | 3.1 |
| | POS(3) | 7.1 | 5.6 | 4.6 | 6.6 | 4.2 | 5.2 | 4.8 | 5.5 |
| | | | Cadence (Steps/Min) | ACC (g's) | VEL (Cm/Sec) | POS (Cm) | | | |

Table 5-VI. Male Subject Peak to Peak Translational Parameters Averaged for 3 Step Cycles per Subject

5.4.3 Pelvic Translation Results: Normal Females in High Heels

The plots and table contained in this section show the translation results for the walking test of female subjects wearing high heeled shoes. The acceleration, ACC, velocity, VEL, and position, POS, of the pelvis are shown for each of the three coordinate axes.

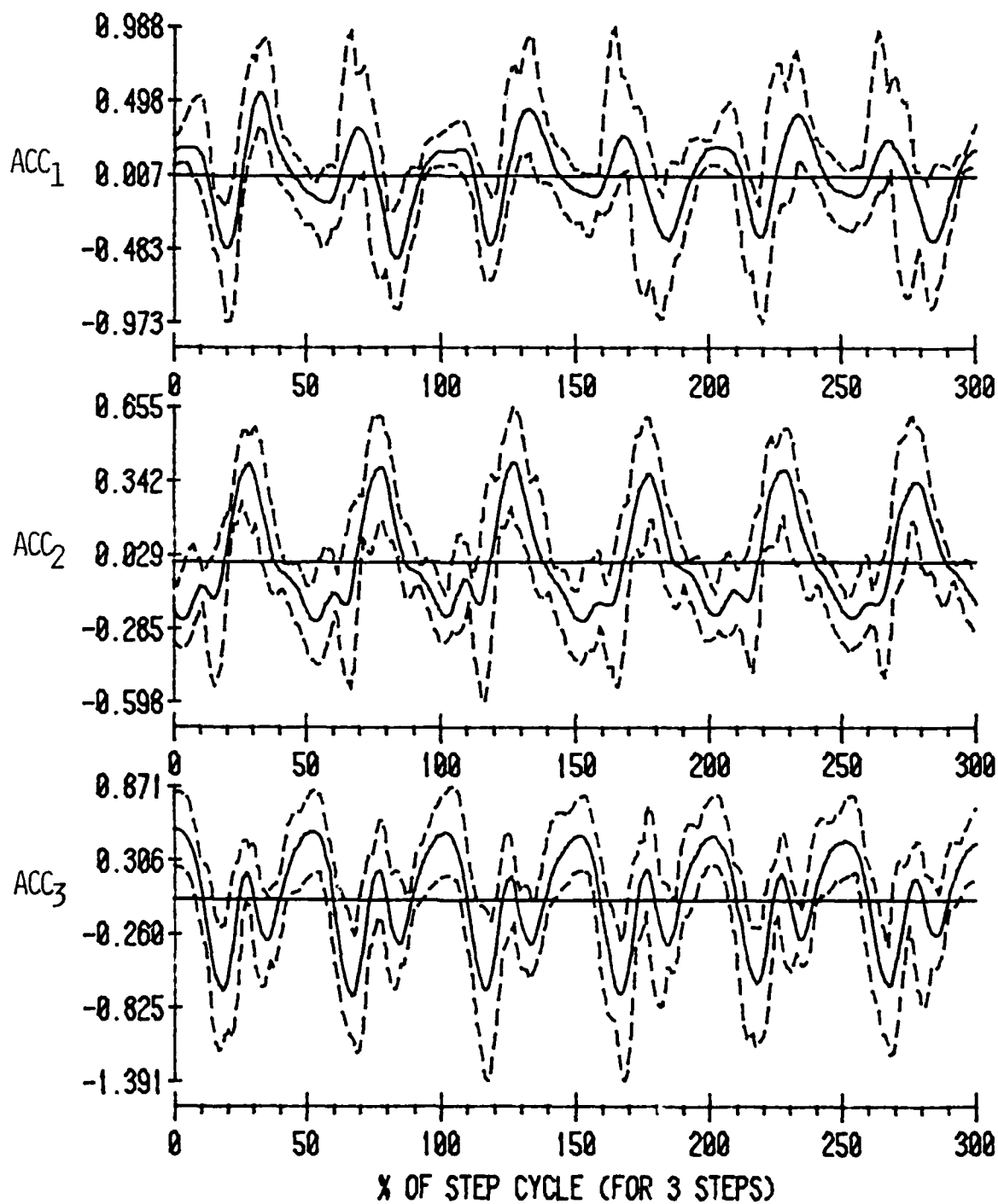


Figure 5-29. Pelvic Acceleration (g's) for Female Subjects Walking in High Heeled Shoes.

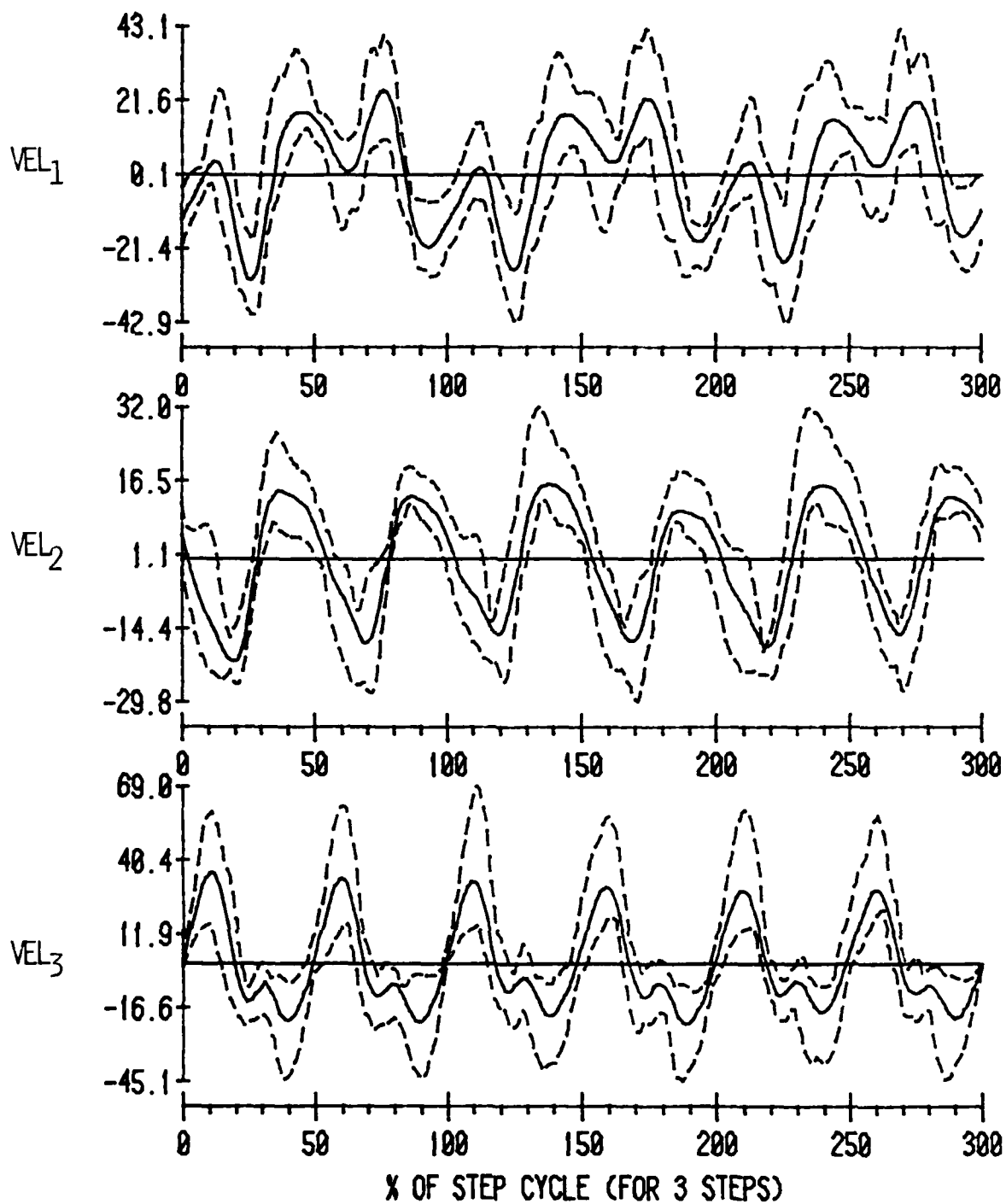


Figure 5-30. Pelvic Velocity (cm/sec) for Female Subjects Walking in High Heeled Shoes.

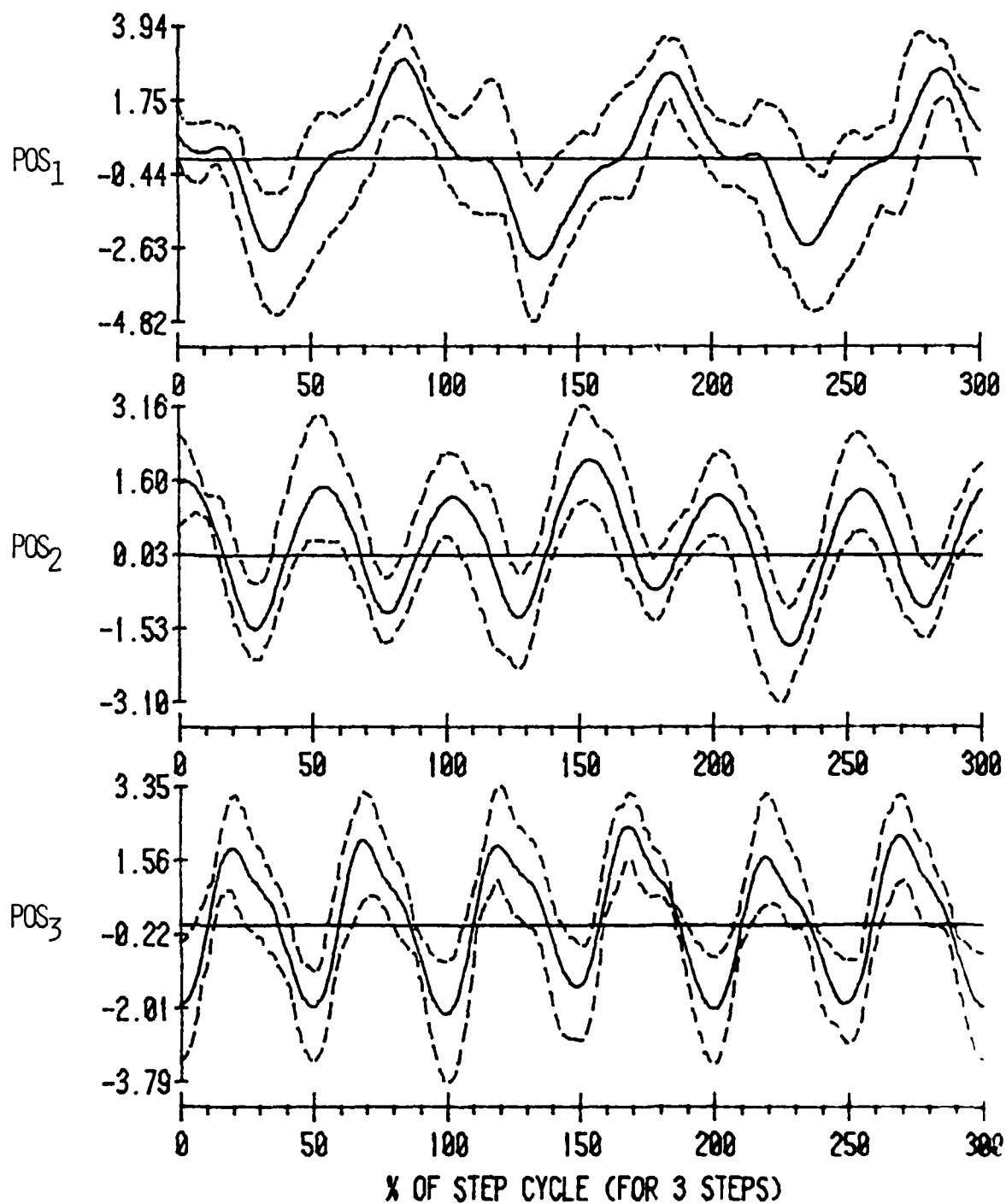


Figure 5-31. Pelvic Position (cm) for Female Subjects Walking in High Heeled Shoes.

| Test 4 | Subject: 8 (High Heeled Shoes) | | 11 | 9 | 12 | 13 | 14 | 10 | Mean |
|--------|-----------------------------------|------|------|---------------------|----------|--------------|----------|-------|------|
| | Cadence | 139 | 131 | 130 | 129 | 141 | 121 | 134 | |
| | ACC(1) | 1.45 | 0.75 | 0.98 | 1.76 | 1.77 | 0.66 | 1.68 | 1.29 |
| | ACC(2) | 0.94 | 0.66 | 0.71 | 0.76 | 1.00 | 0.64 | 1.12 | 0.83 |
| | ACC(3) | 1.76 | 0.64 | 1.22 | 1.44 | 1.72 | 0.95 | 1.98 | 1.39 |
| | VEL(1) | 70.2 | 45.3 | 47.3 | 80.7 | 69.0 | 48.8 | 72.6 | 62.0 |
| | VEL(2) | 54.3 | 41.3 | 40.4 | 44.6 | 35.7 | 38.5 | 45.1 | 42.8 |
| | VEL(3) | 76.7 | 31.0 | 59.5 | 67.4 | 91.0 | 41.9 | 100.7 | 66.9 |
| | POS(1) | 5.0 | 5.4 | 4.2 | 8.0 | 5.6 | 6.1 | 6.9 | 5.9 |
| | POS(2) | 3.8 | 2.8 | 3.3 | 4.1 | 2.0 | 3.2 | 2.5 | 3.1 |
| | POS(3) | 4.9 | 2.4 | 3.9 | 4.5 | 5.1 | 2.6 | 6.5 | 4.3 |
| | | | | Cadence (Steps/Min) | ACC(g's) | VEL (Cm/Sec) | POS (Cm) | | |

Table 5-VII. Female Subject Peak to Peak Translational Parameters
Averaged for 3 Step Cycles per Subject.

5.4.4 Pelvic Translation Results: Normal Males with Back Load

The plots and table contained in this section show the translation results for the walking test of male subjects wearing shoes and carrying a 13.6 Kg load on their back. The acceleration, ACC, velocity, VEL, and position, POS, of the pelvis are shown for each of the three coordinate axes.

A discussion of the results presented in this chapter and a comparison of the results of this study with those reported by other researchers is contained in the following chapter.

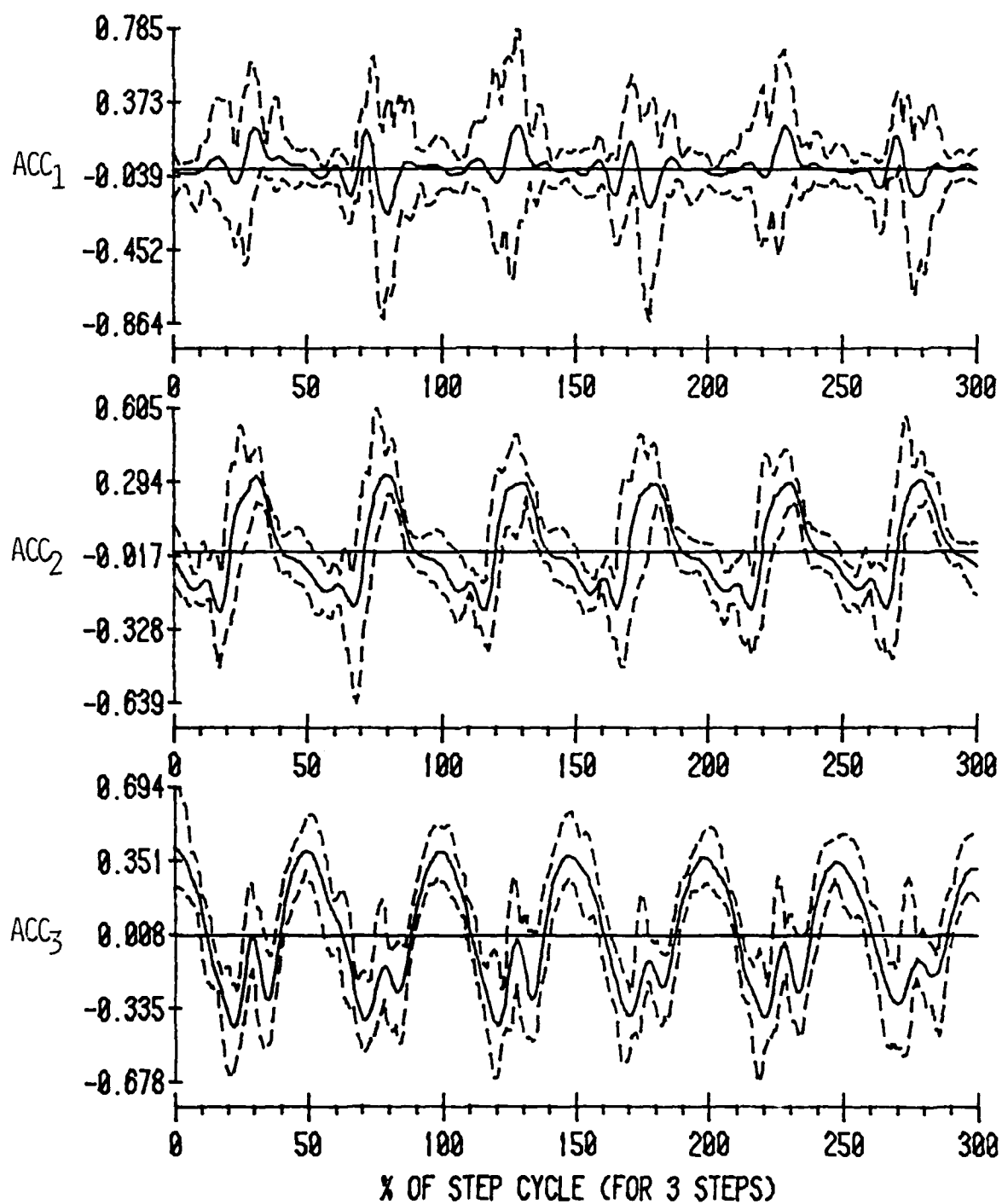


Figure 5-32. Pelvic Acceleration (g's) for Male Subjects
Walking in Shoes with a Back Load.

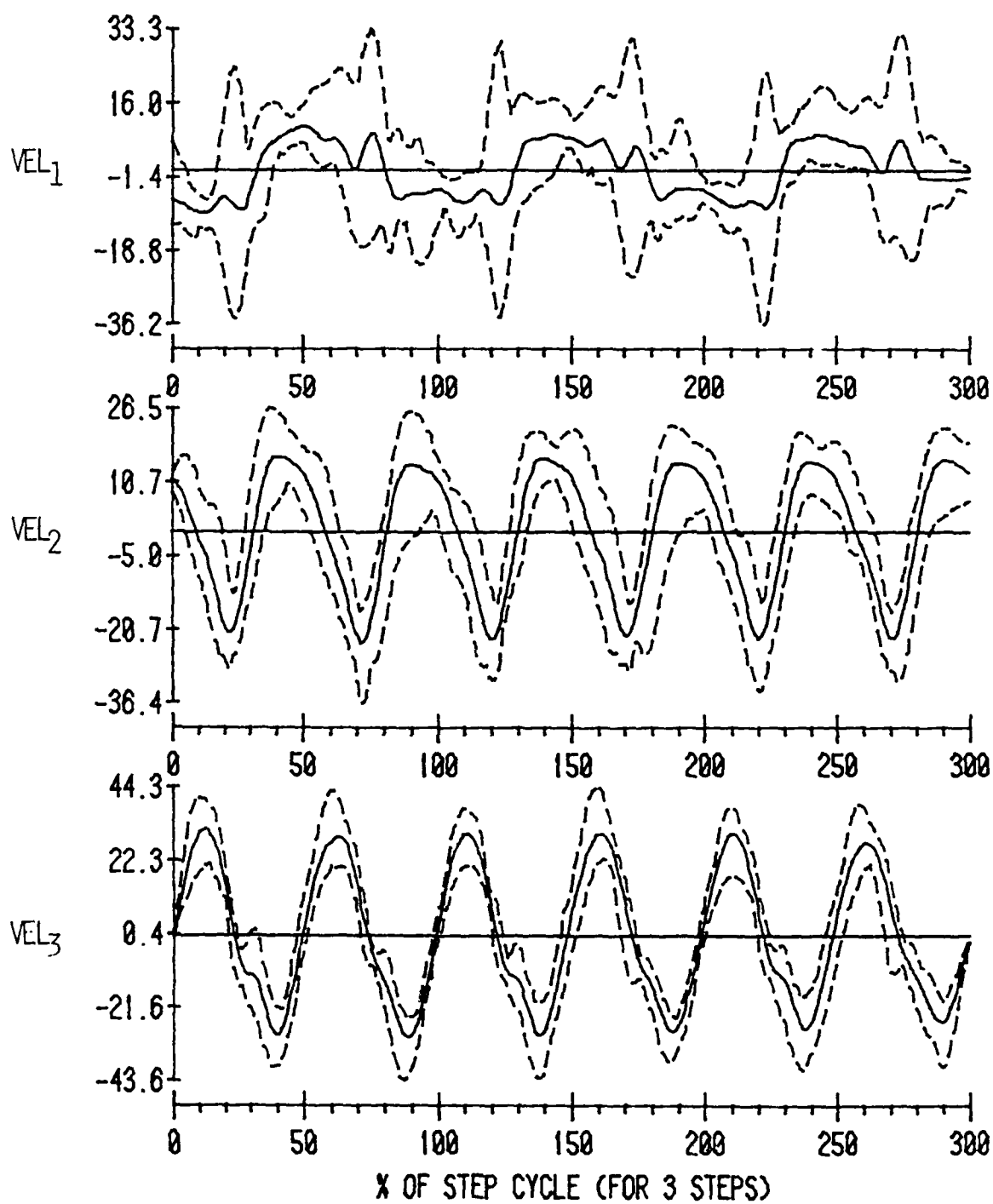


Figure 5-33. Pelvic Velocity (cm/sec) for Male Subjects Walking in Shoes with a Back Load.

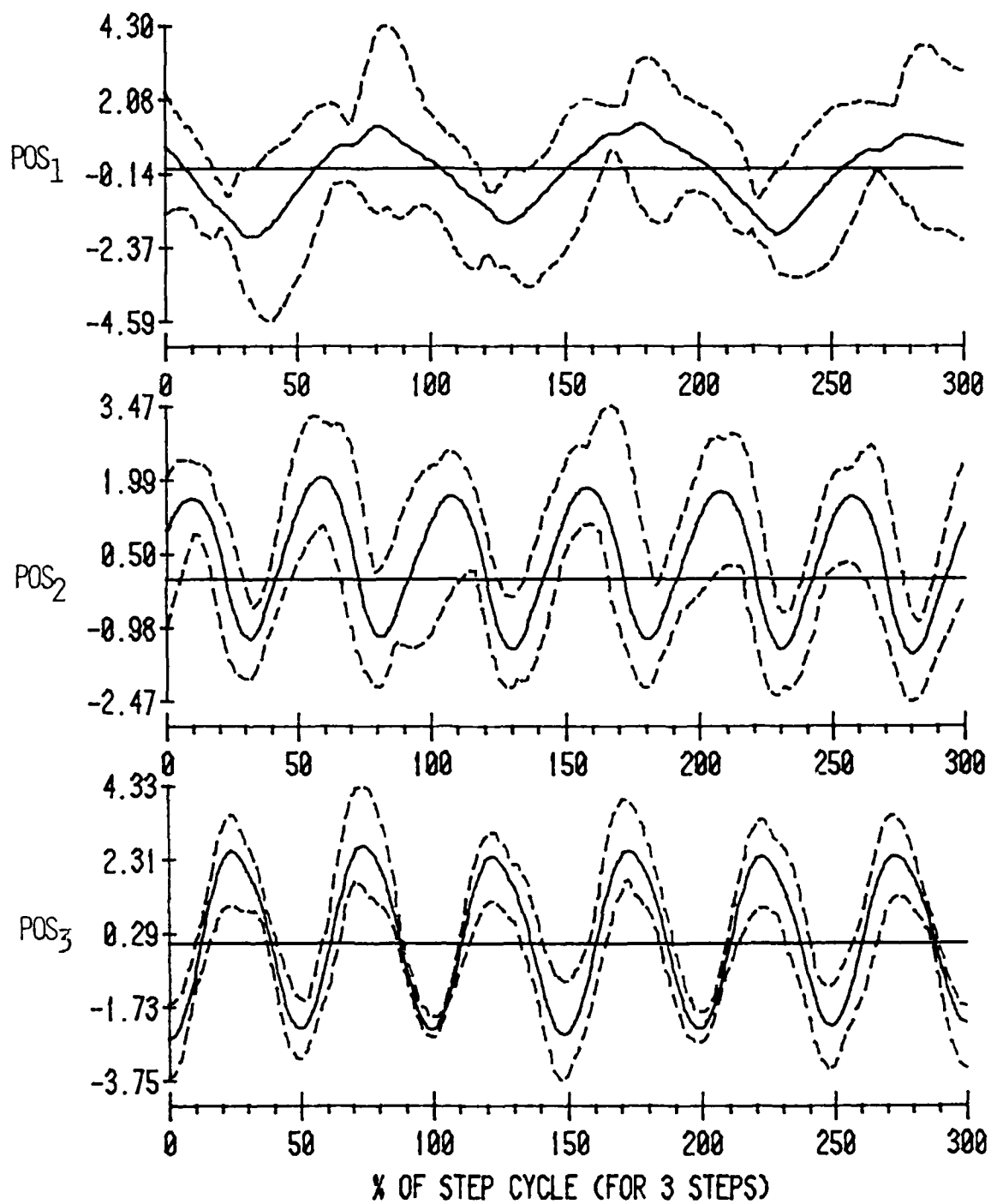


Figure 5-34. Pelvic Position (cm) for Male Subjects Walking in Shoes with a Back Load.

| Test 3 | Subject: 5 | | 3 | 2 | 4 | 6 | 7 | 1 | Mean |
|--------|-----------------|------|---------------------|------|-----------|--------------|----------|------|------|
| | (Carrying Load) | | | | | | | | |
| | Cadence | 118 | 110 | 98 | 115 | 114 | 110 | 105 | |
| | ACC(1) | 1.19 | 1.03 | 0.68 | 0.80 | 1.08 | 1.56 | 0.81 | 1.02 |
| | ACC(2) | 0.93 | 0.87 | 0.60 | 0.74 | 0.68 | 0.67 | 0.52 | 0.72 |
| | ACC(3) | 1.04 | 0.87 | 0.65 | 1.05 | 0.98 | 0.75 | 0.76 | 0.87 |
| | VEL(1) | 34.2 | 48.6 | 24.2 | 32.2 | 68.4 | 52.7 | 29.0 | 41.3 |
| | VEL(2) | 45.8 | 49.6 | 45.6 | 45.3 | 42.1 | 46.2 | 37.1 | 44.0 |
| | VEL(3) | 72.7 | 67.7 | 50.6 | 79.8 | 53.9 | 50.4 | 51.4 | 60.9 |
| | POS(1) | 3.9 | 4.7 | 1.9 | 4.4 | 7.8 | 5.9 | 4.2 | 4.7 |
| | POS(2) | 3.1 | 3.8 | 3.8 | 3.8 | 3.7 | 3.9 | 3.5 | 3.6 |
| | POS(3) | 5.5 | 6.0 | 5.5 | 6.3 | 4.1 | 4.4 | 4.9 | 5.2 |
| | | | Cadence (Steps/Min) | | ACC (g's) | VEL (Cm/Sec) | POS (Cm) | | |

Table 5-VIII. Male Subject Peak to Peak Translational Parameters
Averaged for 3 Step Cycles per Subject

Chapter 6

DISCUSSION OF RESULTS

- 6.1 Introduction
- 6.2 Comparison of Results with Previous Studies
- 6.3 Effectiveness in Detecting Changes in Pelvic Motion
- 6.4 Observations from Visual Interpretation of the Results

6.1 Introduction

A discussion of the results, limited to the scope of this study, is presented in this chapter. The measurement results obtained using the accelerometer method are compared to results obtained in the studies by previous researchers which were discussed in chapter 1. The second section contains an analysis of the effectiveness of the accelerometer method in detecting changes in pelvic motion using a nonparametric statistical method. In the final section, some general observations from visual interpretation of the plots contained in chapter 5 are presented.

| | <u>Number of Subjects</u> | <u>Transverse Plane Rotation</u> | <u>Sagittal Plane Rotation</u> | <u>Coronal Plane Rotation</u> |
|-------------------------------------|-----------------------------------|--|--|---------------------------------------|
| Previous Studies (female): | | | | |
| Murray, et.al. (1970) Low-Heels | 30 | 9.6° (2σ ± .8°) | 5.0° (2σ ± .6°) | |
| Murray, et.al. (1970) High-Heels | 30 | 10.0° (2σ ± .7°) | 4.7° (2σ ± .7°) | |
| Previous Studies (male): | | | | |
| Levens, et.al. (1948) | 12 | 7.7° | | |
| Murray, et.al. (1964) | 60 | 10° ± 3.5° | 6° | |
| Murray, et.al. (1966) | 30 | 11.5° ± 3.8° | 6° | |
| Klopsteg & Wilson (1968) | 12 | | | 8° |
| Murray, et.al. (1969) | 64 | 9.0° ± 4.0° | 4.0° ± 0.3° | |
| Lamoreux (1971) | 1 | 10.4° ± 2.0° | 6.9° ± 3.0° | 6.1° ± 1.0° |
| This Study: | | | | |
| Female (barefoot) | 7 | 10.0° (20.3/4.1) | 4.8° (8.5/1.8) | 12.7° (18.8/8.6) |
| Female (low heel shoes) | 7 | 9.0° (18.3/5.1) | 4.4° (7.6/2.0) | 11.0° (17.3/6.5) |
| Female (high heel shoes) | 7 | 9.5° (15.2/4.2) | 5.3° (8.7/1.9) | 13.0° (17.6/9.9) |
| Male (barefoot) | 7 | 6.6° (14.8/3.7) | 3.6° (5.3/2.6) | 7.2° (10.9/4.3) |
| Male (shoes) | 7 | 6.7° (14.5/2.7) | 3.3° (4.9/2.2) | 7.3° (10.9/4.3) |
| (Maximum/Minimum) | | | | |

Table 6-I. Pelvic Rotation Angles for Previous Studies
and This Study.

6.2 Comparison of Results with Previous Studies

In this section the pelvic rotation angles and displacements reported in previous studies will be compared with the results obtained in this study. Since no studies measuring angular velocity, translational acceleration and velocity and male subjects carrying back loads were found, comparisons cannot be made for these measurements. The purpose of the comparisons made in this section was to establish that the accelerometer method developed in this study produced results comparable to other studies. The number of subjects tested was too few to allow more than a subjective comparison. Therefore, a determination of the system accuracy and the establishment of normal values for the subjects was not accomplished.

The pelvic rotation angles reported in previous studies and those measured in this study are shown in Table 6-1. In general, these rotation angles compare very favorably and support the validity of the measurements obtained using the accelerometer method developed in this study. A careful examination of the data in Table 6-1 reveals some significant relationships.

The only previous study of pelvic motion of female subjects was reported by Murray, et.al. in 1970. The transverse and sagittal plane pelvic rotations were measured for level walking in both low and high heeled shoes. The mean transverse pelvic rotation measured was 9.6° in low heels and 10.0° in high heels; the same rotations measured in this study with accelerometers were 9.0° in low heels and 9.5° in high heels. The mean sagittal pelvic rotations reported by Murray, et.al. were 5.0° in low heels and 4.7° in high heels compared to the accelerometer results in this study of 4.4° in low heels and 5.3° in high heels. The results obtained in this study showed very good agreement with the results reported by Murray, et.al. for female subjects.

The results for male subject studies are also shown in Table 6-1. The male subjects were tested wearing shoes in all the previous studies. In this study, the mean transverse pelvic rotation was found to be 6.6° for males walking barefoot and 6.7° for males wearing shoes. Levens, et.al.(1948) reported this rotation to be 7.7° . The three studies by Murray, et.al. and the study of one subject by Lamoreux reported values from $9.0^{\circ} \pm 4.0^{\circ}$ to $11.5^{\circ} \pm 3.8^{\circ}$. The mean values obtained in this study were smaller, but are still within the range of values reported in the previous studies. In addition, Murray, et.al.(1964) reported a mean value of 6.4° for male subjects of medium height; five of the seven subjects tested with the accelerometer method in this study were of medium height. This difference in height, coupled with the small number of subjects tested, may account for the differences. If the range of measured values are compared, 2.7° to 14.8° for this study and 5.0° to 15.3° for previous studies, then the accelerometer method developed in this study clearly produced results comparable with those from previous studies.

When the sagittal pelvic rotations are compared, the results again compare favorably. Murray, et.al. report in their early studies a value of 6° , but in their latest study(1969) a value of $4.0^{\circ} \pm 0.3^{\circ}$ was reported. Lamoreux reported, for the one subject he tested, a sagittal rotation of $6.9^{\circ} \pm 3.0^{\circ}$. For this study, mean values of 3.6° for barefoot and 3.3° for walking in shoes were measured; the range of measurements was from 2.2° to 5.3° .

Coronal plane pelvic rotation results from the University of California at Berkeley study were reported in Klopsteg and Wilson(1968) as having a mean value of 8° . Lamoreux reported a value of $6.1^{\circ} \pm 1.0^{\circ}$ in his 1971 study. The mean value measured with the accelerometer method in this study was 7.2° for barefoot and 7.3° for walking in shoes with a range from 4.3° to 10.9° . These results show very good agreement.

| Previous Studies: | <u>Number of Subjects</u> | <u>Right/Left Displacement</u> | <u>Anterior/ Posterior Displacement</u> | <u>Vertical Displacement</u> |
|-----------------------|-----------------------------------|------------------------------------|---|----------------------------------|
| Lamoreux (1971) | 1 | 3.4 cm | 4.0 cm | 4.2 cm |
| Waters, et.al. (1973) | 5 | 2.6 cm | 4.5 cm | 4.2 cm |
| This Study: | | | | |
| Male (barefoot) | 7 | 3.2 cm (4.1/2.3) | 3.8 cm (5.9/2.2) | 5.1 cm (7.1/3.6) |
| Male (shoes) | 7 | 3.1 cm (3.7/2.7) | 4.8 cm (6.6/3.1) | 5.5 cm (7.1/4.2) |

(Maximum/Minimum)

Table 6-II. Male Subject Pelvic Displacements for
Previous Studies and This Study.

Only two previous studies of pelvic position have been reported, Lamoreux(1971) and Waters, et.al.(1973). Both of these studies were accomplished with the subjects walking on a treadmill in contrast to the free level walking used in this study. The results of these studies and the present study are shown in Table 6-II. Lamoreux and Waters, et.al. reported right/left pelvic displacements of 3.4 and 2.6 cm while the results from this study were 3.2 cm(barefoot) and 3.1 cm(shoes). These previous studies found the anterior/posterior displacement to be 4.0 and 4.5 cm compared to 3.8 cm(barefoot) and 4.8 cm(shoes) measured in this study. Both Lamoreux and Waters, et.al. reported the vertical pelvic displacement to be 4.2 cm; values of 5.1 cm(barefoot) and 5.5 cm(shoes) were measured with the accelerometer method of this study. The agreement between these three studies is very good despite the limited number of subjects tested.

Although only a small number of subjects were tested with the accelerometer method developed in this study, and only a limited number of previous studies of pelvic motion have been reported, the results obtained with the accelerometer method are comparable to those obtained using other measurement methods.

6.3 Effectiveness in Detecting Changes in Pelvic Motion

The limited number of subjects tested precluded the use of the standard parametric statistical tests to evaluate the results. The following conditions must be met to apply parametric statistical methods of analysis:

- (1) The measurements must be independent.
- (2) The measurements must be drawn from normally distributed populations.
- (3) These populations must have the same variance.

When using parametric statistical methods, it is often assumed that if a sufficiently large number of subjects are tested, then conditions (2) and (3) are true. Seven subjects is not a sufficiently large enough number to make this assumption. Therefore, a nonparametric statistical test was used to determine the effectiveness of the accelerometer method in detecting changes in pelvic motion.

The use of any statistical test requires a statement of the null hypothesis and the selection of a test and level of significance. The null hypothesis is normally formulated for the purpose of being rejected. The null hypothesis for this study was:

The accelerometer method developed in this study cannot detect changes in pelvic motion parameters between:

- (1) female subjects walking barefoot, in low heeled shoes, in high heeled shoes
- (2) male subjects walking barefoot, in shoes, carrying a load on their back.

This hypothesis implied that the measured values of the pelvic motion parameters would not be significantly different between the same subject performing level walking with different footwear or while carrying a load on the back.

| Hypothesis | ω_1 | ω_2 | ω_3 | θ | ϕ | β | Acceleration | | | Velocity | | | Position | | |
|------------|-------------|------------|--------------|--------------|--------|--------------|--------------|-------------|-------------|-------------|------|-------------|-------------|------|-------------|
| | | | | | | | (1) | (2) | (3) | (1) | (2) | (3) | (1) | (2) | (3) |
| A | .148 | .711 | .859 | <u>.008*</u> | .750 | .867 | .492 | .109 | <u>.031</u> | .156 | .063 | <u>.008</u> | .008 | .242 | <u>.023</u> |
| B | <u>.031</u> | .180 | .078 | <u>.016</u> | .055 | .297 | .273 | <u>.023</u> | <u>.008</u> | .195 | .250 | .063 | <u>.031</u> | .117 | .469 |
| C | .422 | .531 | .391 | .567 | .750 | .352 | .125 | .227 | .102 | <u>.016</u> | .297 | <u>.047</u> | <u>.008</u> | .727 | <u>.039</u> |
| D | .195 | .617 | <u>.016*</u> | .539 | .055 | <u>.023*</u> | .273 | .086 | .852 | .781 | .086 | .930 | .594 | .016 | .727 |

*Indicates that this is an inverse probability

Hypothesis A: The pelvic motion parameters for female subjects measured when walking in low heel shoes are greater than when walking barefoot.

Hypothesis B: The pelvic motion parameters for female subjects measured when walking in high heel shoes are greater than when walking in low heel shoes.

Hypothesis C: The pelvic motion parameters for male subjects measured when walking in shoes are greater than when walking barefoot.

Hypothesis D: The pelvic motion parameters for male subjects measured when walking in shoes and carrying a load on their back are greater than when walking in shoes.

Table 6-III. Table of Probabilities Computed Using the Randomization Test for Matched Pairs on Measured Pelvic Motion Parameter Data.

The randomization test for matched pairs was used in this study to test the null hypothesis. The exact probability associated with the occurrence of the measured results can be calculated with a randomization test. The only requirements which must be met are: the measurements must be independent and have numerical meaning in at least an interval sense. The measurements made in this study fulfilled these requirements. The randomization test uses all the information in the measurement data and is 100 percent efficient on data which may be analyzed using the standard parametric t test. Therefore, the randomization test has the same power to reject the null hypothesis as the t test without assuming a normally distributed population with the same variance. An excellent description of the specific details on applying the randomization test for matched pairs is contained in Siegel(1956) and this textbook should be consulted for the specific details of the method.

The results of applying the randomization test to the measured results obtained in this study are shown in Table 6-III. The table contains the calculated probability of occurrence for each of the measured parameters under the hypotheses stated. These hypotheses were formulated as alternatives to the null hypothesis previously stated. Under the null hypothesis, no significant differences between measurements should occur. Therefore, the tests should produce no probabilities less than the level of significance.

The probabilities below a level of significance of 0.05 are underlined in Table 6-III. In 17 cases, at a level of significance of 0.05, a significant difference between the measured data was observed. Therefore, the null hypothesis could have been rejected with a probability of 0.05 that it was falsely rejected. If the probabilities are examined for values below a level of significance of 0.01, five parameters show a

significant difference. Therefore, the null hypothesis was rejected with a confidence level of 99 percent.

Based on this statistical analysis, the accelerometer method developed in this study was effective in detecting changes in pelvic motion.

6.4 Observations from Visual Interpretation of the Results

In addition to calculating numerical results from the measured data, there are some interesting observations which can be made by visual interpretation of the plots. By observing the differences in general curve shape between the mean and extreme values, it is possible to assess subjectively the variation between individuals for a particular pelvic motion parameter. The most striking example of this was the difference in the sagittal plane rotation angle(θ) for female subjects walking barefoot and in low heeled shoes. Examining the plot of theta in Figure 5-8, it was apparent that the mean, maximum and minimum curves all had the same basic shape. Therefore, the seven female subjects walked with the same sagittal plane motion and the major variation between individual subjects was the amplitude, or total degrees of rotation. Observing the same parameter in Figure 5-6, it was obvious that the shape of the three curves was not the same. Therefore, not only did the amplitude vary from individual to individual, but the manner in which individual female subjects rotated their pelvis in the sagittal plane varied. From these observations, one may conclude that female subjects exhibit greater individuality in sagittal plane pelvic rotation walking barefoot than they do in low heeled shoes.

Extending this method of visual interpretation, the following observations were made concerning the pelvic motion parameters measured in this study:

- (1) If variation between individual subjects was observed in the rotation angles, this variation would be greater in the corresponding angular velocity.
- (2) If variation between individual subjects was observed in pelvic position, this variation would be greater in the corresponding velocity, and even greater in the corresponding acceleration.

These observations, although based on a limited number of subjects, suggest that a researcher, or clinician, should use caution in selecting a particular parameter of pelvic motion for analysis. Similar caution should be exercised in attempting to analyze the results of measuring a particular parameter. For example, if the purpose of testing a subject was to determine if the subjects pelvic motion was normal, then a comparison of pelvic position would be more suitable than a comparison of pelvic angular velocity. In testing for "normality", a parameter which showed very little difference between subjects should be chosen. However, if the purpose of testing was to determine if a change in an individuals pelvic motion occurred due to some modification to the lower limb, such as applying an orthosis, it would be more appropriate to select a parameter such as angular velocity or translational acceleration. These parameters are more individualized and therefore small variations in pelvic motion would be more readily discernible.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

- 7.1 Introduction
- 7.2 Conclusions
- 7.3 Recommendations

7.1 Introduction

Studies of human locomotion have been undertaken for various reasons. The earliest studies were probably begun with a desire to acquire new knowledge and a curiosity of the unknown. Most of the modern studies have been related to improving our understanding of normal walking and the problems associated with pathological gait. Any attempt to restore normal functioning when the locomotor system is damaged must be based on accurate knowledge of the functions of the parts of the body involved. This includes surgical procedures to repair, or replace, the damaged bones, joints or muscles and physiotherapy to improve the functioning of impaired lower limbs. When irreparable damage occurs, the normal locomotor system must be supported externally or replaced. The design of orthotic and prosthetic devices should rely on sound mechanical principles and be aimed at restoring near normal functioning of the locomotor system. Any improvement in surgical procedures, physiotherapy techniques, orthoses or prostheses depends on better knowledge of how the locomotor system functions.

The vast majority of the studies of human locomotion have focused on defining the motion of the lower limbs. The study begun in 1947 at the University of California at Berkeley was very comprehensive and clearly identified the overall motion of the lower limbs during walking. This study also began the development of modern techniques to evaluate the

design and function of orthoses and prostheses. Other studies have further refined and added to our knowledge of the positions of the lower limbs during various locomotion activities. Although the literature contains many references to the importance of understanding the movement of the pelvis in both normal and pathological gait, there have been very few studies devoted to this end.

In this final chapter, the conclusions reached during this study of the kinematics of the pelvis and some recommendations for the future use of the accelerometer measurement system are presented.

7.2 Conclusions

In all the previous studies reporting on pelvic motion, the pelvic parameters were measured only as a small part of a larger study of lower limb motion. The studies by Murray, et.al. discussed in chapters 1 and 5 were the only studies of pelvic motion conducted on a large number of subjects. However, only two pelvic motion parameters were measured: pelvic rotation in the transverse and sagittal planes. Only Lamoreux's study measured all six pelvic motion orientation and position parameters and his values were based on repeated tests of one subject walking on a treadmill. As a result, the movement of the pelvis during human locomotion activities has been defined only in very general terms.

This study was undertaken as a first step in determining, with greater precision, how the pelvis moves during normal and pathological human locomotion activities. The purpose was to develop a kinematic measurement system capable of measuring the three dimensional rotation and translation of the pelvis during walking. The system also had to be capable of detecting changes in pelvic motion due to disorders of the lower limbs. A planar eight accelerometer kinematic measurement system was developed and tested which fulfilled the purpose of this study.

The accelerometer measurement system was tested experimentally; the test results were reported in chapter 4. The system was also tested on male and female subjects during level walking activities and a comparison of the walking test results with previous studies was made in chapter 6. These tests established that the accelerometer measurement system produced results very comparable to those obtained using different measurement systems. A statistical analysis, also reported in chapter 6, clearly demonstrated that the accelerometer measurement system was capable of detecting changes in pelvic motion.

In addition to measuring the orientation and position of the pelvis in three dimensions, the accelerometer method developed in this study also measures the angular velocity and translational acceleration and velocity of the pelvis. As discussed in chapter 6, these parameters appear to vary more than the orientation and position parameters from individual to individual and would provide additional information on pelvic motion which could prove particularly useful in studies of pathological gait. From the description in chapter 4, the experimental method of calibrating the system, collecting subject data and processing data may have appeared complex and time consuming. However, with minimal training and practice, a researcher should be able to complete the walking tests and data processing for a subject within one hour.

Some recommendations for the future use of the accelerometer measurement system developed in this study will be presented in the next section.

7.3 Recommendations

In this section three general recommendations for the future of the accelerometer measurement system developed in this study will be discussed. The first concerns the use of the present system, the second suggests improvements which should be made to the accelerometers and the third proposes some additional areas of kinematic measurement where the method developed in this study could be applied.

The pelvic motion measurement system developed in this study should be used in a clinical research environment, such as the Oxford Orthopaedic Engineering Centre. This environment would provide the opportunity for collaborative studies with orthopaedic surgeons on disorders of the lower limbs. The initial studies should include as many normal subjects as possible to provide the necessary statistical basis for establishing the range of pelvic motion for normal healthy subjects. In addition to studies of orthopaedic disorders, the system could also be used to evaluate orthotic devices applied to the lower limbs. These devices include braces and other mechanical supports for the lower limbs and orthopaedic shoes. By measuring the pelvic motion of a subject wearing different orthoses, it would be possible to provide quantitative data for evaluating the effectiveness of various orthoses designed for the same purpose.

The current accelerometer system performed very well and provided satisfactory results. However, there were problems in fabricating and assembling the accelerometers. The silicon beam sensing elements are very fragile and 6 of 18 were broken during assembly in spite of working very carefully under a microscope. Another problem was containing the silicon fluid within the accelerometer housing. Silicon is a well known release agent and is contained only with carefully designed seals. The method of applying a silicon compound to the ends of the accelerometer housing was not the most effective method of containing the fluid. If more

Operating range: ± 10 g's
Sensitivity: ± 2 mv/v/g $\pm 25\%$
Cross axis sensitivity: $<2\%$ FS
Non-linearity and hysteresis: $<1\%$ FS
Resonant frequency: approximately 200 Hz
Operating temperature range: -40 to $+85$ °C
Nominal resistance: 1000 ohms
Resistance matching: $<10\%$
Operating voltage: 10 volts maximum
Thermal sensitivity shift: $-0.2\%/^{\circ}\text{C}$
Thermal zero shift: $<0.005\%$ of FS/ $^{\circ}\text{C}$
Damping: 0.5 - 1.0
Weight: 3 grams

Table 7-I. AME Modified AE864C Specifications

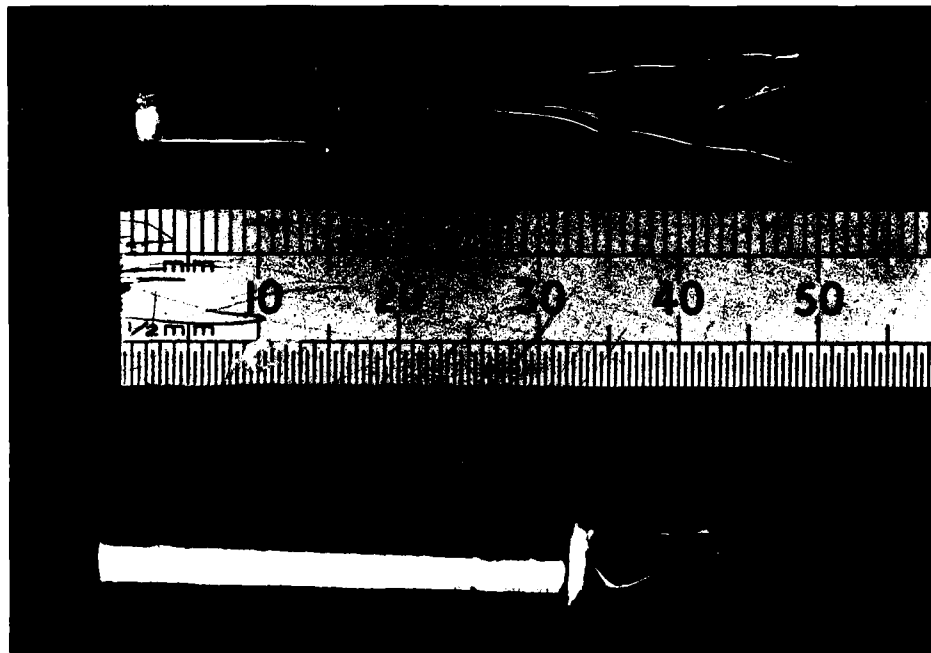


Figure 7-1. AME Modified AE864C Accelerometer and the Accelerometer used in this Study.

accelerometers were to be fabricated, the current design should be modified to provide adequate mechanical seals.

During this study there has been correspondence with AME of Norway, the manufacturers of the silicon beam sensing elements, on a variety of subjects. In a letter in December 1977 the production manager indicated the company was considering production of a ± 10 g accelerometer (previously the lowest range was ± 75 g) and sample quantities would be available in February 1978. With further communication on this subject they agreed to supply a modified version of the AE864C ± 75 g accelerometer with specifications shown in Table 7-1. In May 1978 two accelerometers were received; the modified AE864C accelerometer and the accelerometer used in this study are shown in Figure 7-1.

Limited tests of the sensitivity and thermal zero shift of the two AE864C accelerometers were conducted. The sensitivity was measured at 0.84 mV/V/g compared to 4.2 mV/V/g for the accelerometer developed in this study. This would not be a problem as the gain of the amplifiers can be increased to provide signals of the proper voltage level. Thermal zero shift tests were performed on two occasions and the results indicated a thermal zero shift of 0.006 %/VFS/ $^{\circ}$ C or 0.0012 g's/ $^{\circ}$ C which was approximately twice the value (in g's/ $^{\circ}$ C) of the accelerometer developed in this study.

Although the thermal zero shift was greater and the sensitivity reduced for the AE864C accelerometer these values were still within the acceptable range for this type of research. The major advantage of the AE864C is its smaller size and weight and the use of this accelerometer would result in a much smaller body mounted measurement package. It is recommended that the AE864C accelerometer be used in any future research.

The accelerometer measurement method developed in this study could also be used in kinematic studies of the motion of other body members. With appropriate modifications for mounting the system, this method could be used to measure the three dimensional motion of the head, thorax, arms or shank. Other studies have made acceleration or position measurements with accelerometers, or targets, attached to these locations. This use of the accelerometer system developed in this study would only be possible if suitable mounting systems were developed. However, such applications could be suitable areas of investigation for future studies.

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AE800 Silicon Element Specifications



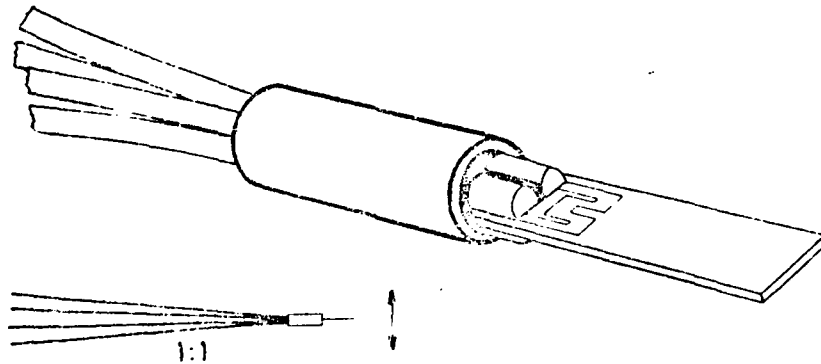
Solid State Products

SEMICONDUCTOR
TRANSDUCER ELEMENTS

AE 801
AE 802
AE 803

The **AKERS** 800 series transducer elements represent an improvement in the measuring and control field. A silicon beam with planar diffused resistors is the active element of this new multipurpose transducer element, which converts force, pressure, movement, acceleration and angle etc. to electrical signals.

A deflection of the beam gives a resistance change in the diffused resistors on both sides of the beam. An electrical signal may be obtained which is nearly proportional to the deflection of the beam.

AE 800 features:

LOW IMPEDANCE
HIGH OUTPUT SIGNAL
SMALL SIZE
HIGH FREQUENCY RESPONSE
EASY MOUNTING

AE 800 applications:

PRESSURE TRANSDUCERS
LOAD CELLS
DEFLECTION TRANSDUCERS
ACCELEROMETERS
INCLINOMETERS
etc.

AE 470/1

A-S AKERS ELECTRONICS

Member of the AKERS GROUP

Address: Horten, Norway • Telephone: 42 651 • Telex: Oslo 6527 • Telegrams: Akerelectro Horten

STRAIN ($1 \mu S$: relative elongation of 10^{-6})

The recommended maximum strain in the beam is $1000 \mu S$, given by the formula:

$$\epsilon_{\max} = 1,5 \cdot h \cdot \frac{f}{L^2}$$

with the same nomenclature as above.

The maximum deflection of the beam corresponds to a resistance change

$\Delta R/R$ of the order of 5-6%.

At 6 volts supply voltage and maximum recommended deflection of the standard size beam, the output voltage will be of the order of 150 mV.

TEMPERATURE EFFECTS

ZERO SHIFT is varying from

$0,005^\circ C$ to $0,05^\circ C$

depending on bridge matching, matching of the diffused resistors and chosen specifications. Normally this effect is so small that it can be neglected.

SENSITIVITY SHIFT is of the order of

$-0,2^\circ C$

when the bridge is voltage fed. Under severe temperature conditions thermistor compensation is recommended in the feeding system.

FREQUENCY RESPONSE

With normal beam dimensions the resonance frequency is approximately 7 kHz. By loading the beam or changing the beam length and thickness, the resonance frequency can be chosen within wide limits.

HANDLING

During handling and mounting care must be taken that the allowable strain is not exceeded. As a limit for the allowable strain in the beam, $1000 \mu S$ has been chosen. During fabrication the element has been tested at $1500 \mu S$ and means should therefore be provided that the maximum strain under no circumstances can exceed $1500 \mu S$. A design which includes the transducerelement, must therefore include means for overload protection. The design should also include provisions for preventing unintended contact with the transducerelement, as this will most certainly lead to destruction of the silicon beam. For mounting purpose cement, brackets or other mechanical arrangement can be used.

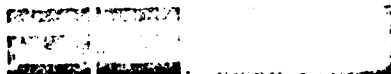
SPECIFICATIONS

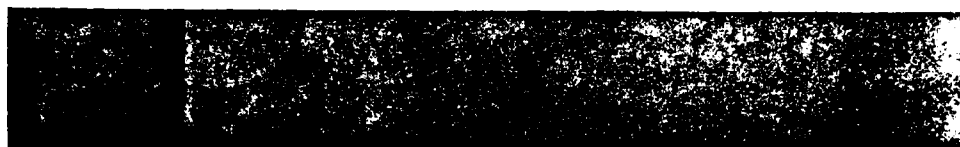
| | |
|---|---|
| Excitation | : 6 V |
| Nominal resistance | : 1000 ohm |
| Nominal resistance matching | : 10% |
| Temperature coefficient of individual resistors | : $0,8 \cdot 10^{-3}$ per $^{\circ}\text{C}$ |
| Output voltage | : 25 mV/V |
| Zero shift of complete element | : AE801P AE802P AE803P : <0.005% <0.02% <0.05% of full scale per $^{\circ}\text{C}$ |
| Gauge factor of individual resistors | : 55 - 70 |
| Temperature coefficient of gauge factor | : $2 \cdot 10^{-3}$ per $^{\circ}\text{C}$ |
| Modules of elasticity | : $1.6 \cdot 10^4$ kp/mm ² |
| Max dissipation | : 4 mW/ $^{\circ}\text{C}$ in oil 1 mW/ $^{\circ}\text{C}$ in free air |
| Non linearity at an output signal of 25 mV/V | : ca. $\pm 0.25\%$ FS. |

MECHANICAL DATA (Standard beam)

| | |
|---------------|---------------------|
| Case : length | : 5 mm |
| : diameter | : 1.8 mm ϕ |
| Beam : length | : 5 mm |
| : width | : 1 mm |
| : thickness | : 0.1 mm $\pm 10\%$ |

Upon request elements with thickness 0.15 mm $\pm 10\%$ can be delivered.





Solid State Products

THE MEASUREMENT OF ACCELERATION USING THE TRANSDUCER ELEMENTS AE 801 - 803

Introduction

1. The transducer element consists of a silicon beam mounted in a special header. The silicon beam has diffused resistors on each side. When the tip of the beam is deflected, the resistors will change their values, thus giving an electrical signal proportional to the deflection.

In order to achieve full scale output from the transducer element a deflection of between 50 and 100 microns is needed. Therefore, if a spring element can be made which gives this deflection when exposed to a physical quantity such as acceleration, the transducer element will transform this deflection to an electrical signal. In the following a brief description of how acceleration measurements can be made with the transducer element is given.

2. Measurement of acceleration

According to Newton's laws of motion, equilibrium always exists between the sum of the external forces acting on a mass and the product of mass and acceleration. It is therefore possible to design an accelerometer by letting the inertial force (product of mass and acceleration) act on a spring and measure the deflection of the spring under influence of the inertial force. The deflection of the spring will then be proportional to the acceleration that the mass is exposed to.

The deflection of the spring element can be measured with the transducer element provided that the spring element is designed to give a deflection which is suitable for the transducer element, - that is 50 - 100 μm .

OR:
/ w/
no
sta

3. Ways of designing accelerometers

Accelerometers made with the transducer element can be separated into 2 groups, accelerometers with the silicon beam as the spring element and accelerometers with other spring elements.

- 3.1 Accelerometers with the silicon beam as the spring element

For very high accelerations the inertial forces from the beam itself will load the beam and deflect it. The sensitivity of the beam alone as an accelerometer is given from the equation below.

AKERS ELECTRONICS

Address: 3191 Horten, Norway - Telephone: 4733 42 651 - Telex: Oslo 16527 - Telegrams: Micro

$$\frac{\Delta U}{U} = 40 \cdot 10^{-10} \frac{L^3 - \ell^3}{h} \cdot \frac{a}{g}$$

where

L = free beam length mm

ℓ = length from tip of beam to the end of the resistors in mm

$(L - \ell = 1 \text{ mm})$

h = beam thickness in mm

$\frac{a}{g}$ = acceleration in g's

The resonance frequency for the free beam is given from the equation below:

$$f = 1,31 \cdot 10^6 \frac{h}{L^2} \quad (h \text{ and } L \text{ in mm give } f \text{ in Hz})$$

The standard beam in the transducer element AE 801-803 with a free length of 4 mm and thickness of 0,1 mm will thus have an acceleration sensitivity of 1500 $\mu\text{V/V/1000 g}$ and a resonance frequency of 8200 Hz.

If an increased sensitivity is desired, a weight can be added at the tip of the beam. The output signal from such an accelerometer can be calculated from the following equation:

$$\frac{\Delta U}{U} = \frac{3 P \cdot \ell'}{b h^2 E} \cdot \lambda$$

where

P = weight of mass under the influence of a given acceleration in kp

ℓ' = distance between centre of gravity of mass and centre of diffused resistors in mm

λ = gaugefactor of resistors

b = width of beam in mm

h = thickness of beam in mm

E = modulus of elasticity of silicon = $1.6 \cdot 10^4 \text{ kp/mm}^2$

The resonance frequency of such an accelerometer configuration can be calculated from the following equation:

$$f = \frac{1}{2\pi} \sqrt{\frac{b h^3 \cdot E}{4 \ell^3 \cdot m}}$$

with the same nomenclature as above but with the addition of:

m = mass of added weight in $\text{kg s}^2/\text{m}$

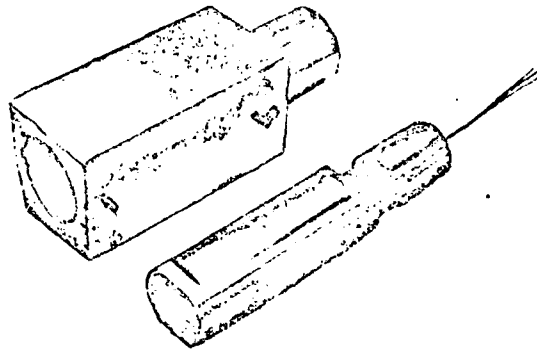
l = distance from centre of gravity of weight to the clamping edge of the beam in mm

3.2

Accelerometers with a separate spring element

Experience has shown that accelerometers should be able to withstand acceleration loads of about 1000 g without damage because such acceleration levels are reached during normal handling. Due to the difficulties in designing stops for accelerometers with added weight at the tip, it is recommended not to make them if they cannot withstand 1000 g.

In this case it is recommended to use a design with a separate spring element. The motion of the spring mass system under influence of acceleration is then detected by the silicon beam and transformed to an electrical signal. In the fig. below one way of designing such a spring mass system is shown. The silicon beam can be preloaded or it is possible to use excitation screws on both sides if a higher output signal is desired.



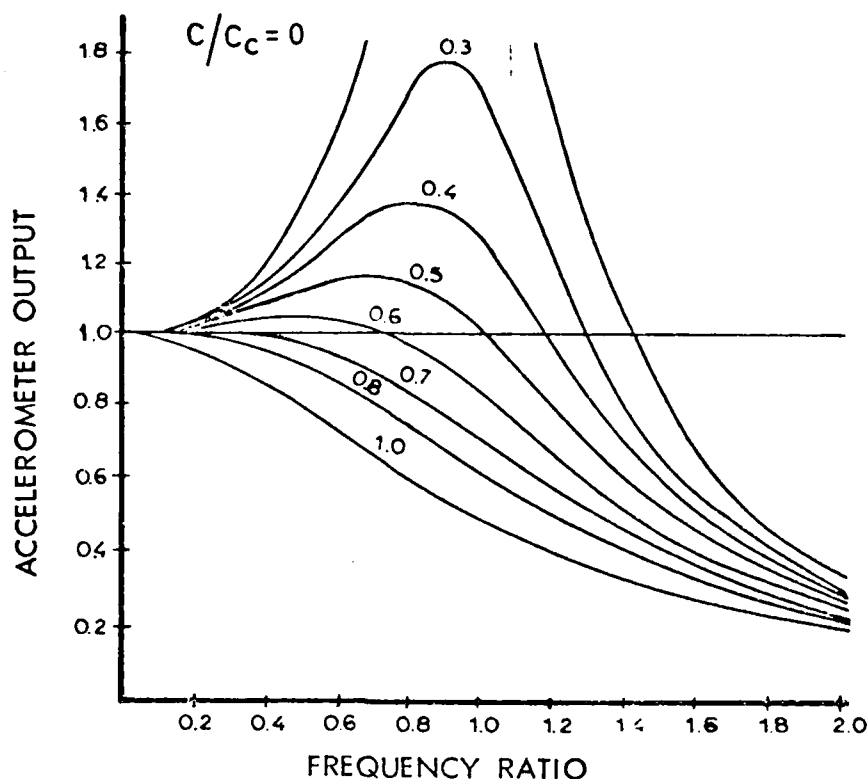
4.

Characteristics of accelerometers

4.1

Frequency response of accelerometers

In the figure below the output signal from an accelerometer exposed to a constant acceleration is given as function of frequency with respect to the resonance frequency and damping.



Accelerometers with the beam are all low damping devices and behave essentially as accelerometers with $c/c_c \approx 0$ (Damping ratios of ≈ 0.02 are typical).

It is possible to increase the damping ratio to, for instance, 0.7 by surrounding the accelerometer with oil, such as silicon oil, with a proper viscosity. This measure effects the sensitivity of the accelerometer and must be taken into account when calculating the sensitivity.

4.2

Temperature effects

Temperature will effect accelerometers equipped with the beam in essentially the same way as it effects the beam alone. The following two effects in the beam are the most significant.

1. Zero-shift of the transducer element. The zero-shift of the transducer element can be selected by selecting elements of the classes 801, 802 and 803.
2. The sensitivity shift of the transducer element amounts to $-0.2\%/^{\circ}\text{C}$ and this means that the output from the transducer element will decrease by 2% for every 10°C the temperature increases.

For a more detailed description of the beam, its behaviour under temperature variations and the circuitry for use with it, an application note titled "The transducer element AE 801 - 803 and how to use it", can be recommended.

5.

Summary

The transducer element AE 801, 802 and 803 are well suited for accelerometer applications and accelerometers with very high ranges and with low ranges can be made. The main advantages of accelerometers made with the transducer element are:

1. Cross sensitivity theoretically = 0
2. Low source impedance
3. Small size
4. Low damping.

steps 12-24

[illegible]

TO: DIRECTOR, FBI
FROM: SAC, NEW YORK
SUBJECT: RAYMOND J. BROWN

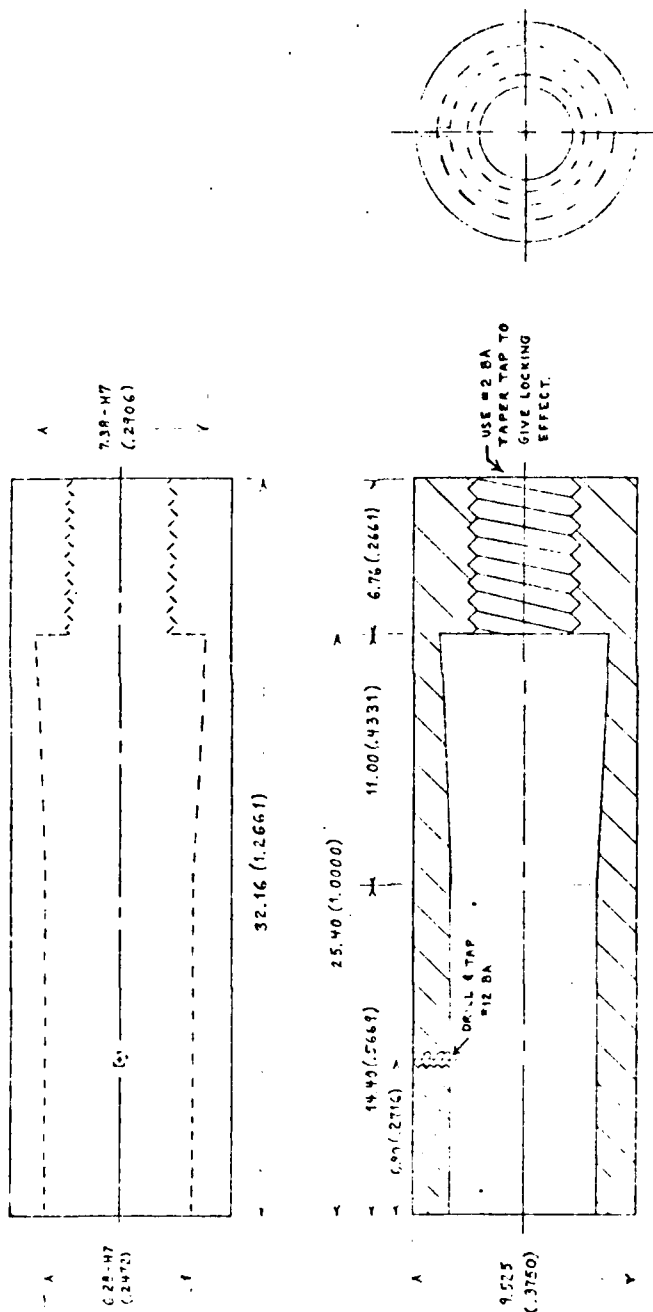
Accelerometer Drawings

NY 70337 R

THIRD ANGLE PROJECTION

HOUSING

TEN OFF



| | | | | | |
|------|--------------|---------------------------|---|--------------------------------|---------------------|
| DATE | MODIFICATION | MATERIALS BRASS FINISH | TOLERANCES .0025 (.0008) UNLESS OTHERWISE SPECIFIED DIMENSIONS : mm (inches) | TITLE | DRAWING No. |
| | | | | 5g ACCELEROMETER (MOD CASE) | - 517-2 A |
| | | SCALE 5:1 | DRN. D.M.H. 16 SEP 76 | TRD. | CHKD. |

100-443888

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AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH
THE DEVELOPMENT OF AN ACCELEROMETER SYSTEM FOR MEASURING PELVIC-- TC(U)

F/G 6 16

1979 D K MCMASTER

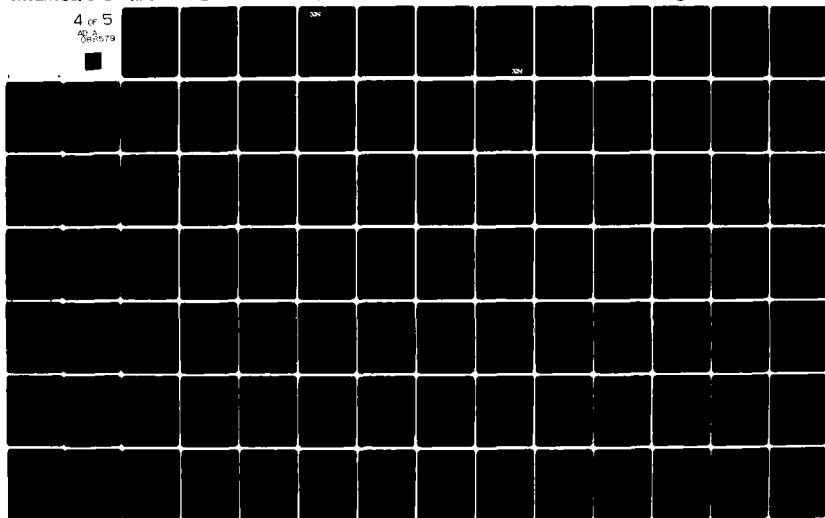
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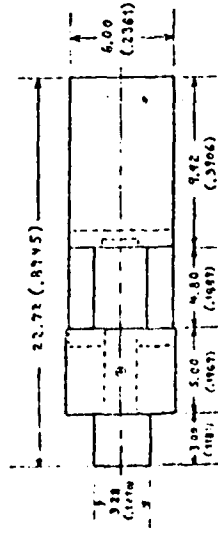
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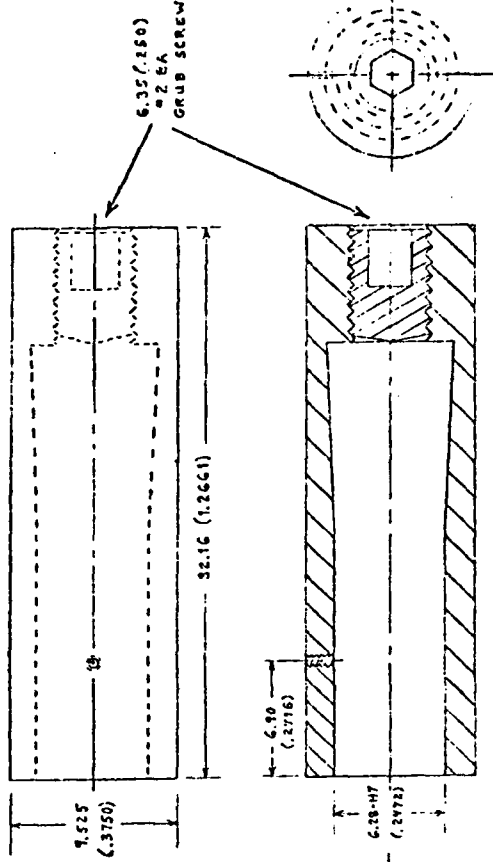
USED ON ORG. No.

THIRD ANGLE PROJECTION
GENERAL ASSEMBLY

SENSING UNIT



HOUSING UNIT



| ISSUE | DATE | MODIFICATION | MATERIALS | TOLERANCES | DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY | |
|-------|------|--------------|--------------------------------|--|--|--|
| | | | SEE DRAWINGS 2 AND 3 FINISH | SEE DRAWING 2 AND 3 DIMENSIONS: mm (inches) | DRAWING No. 5.1:1 | |
| | | | SCALE 3.75:1 | TRD. | 5g ACCELEROMETER (MOD CASE) | |
| | | | DRN, DKM 17 SEP 76 | CHKD. | A | |

NY 70337A

USED ON DRG. No.

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(1.524)

THIRD ANGLE PROJECTION

ONE OFF

3.175
(.125)

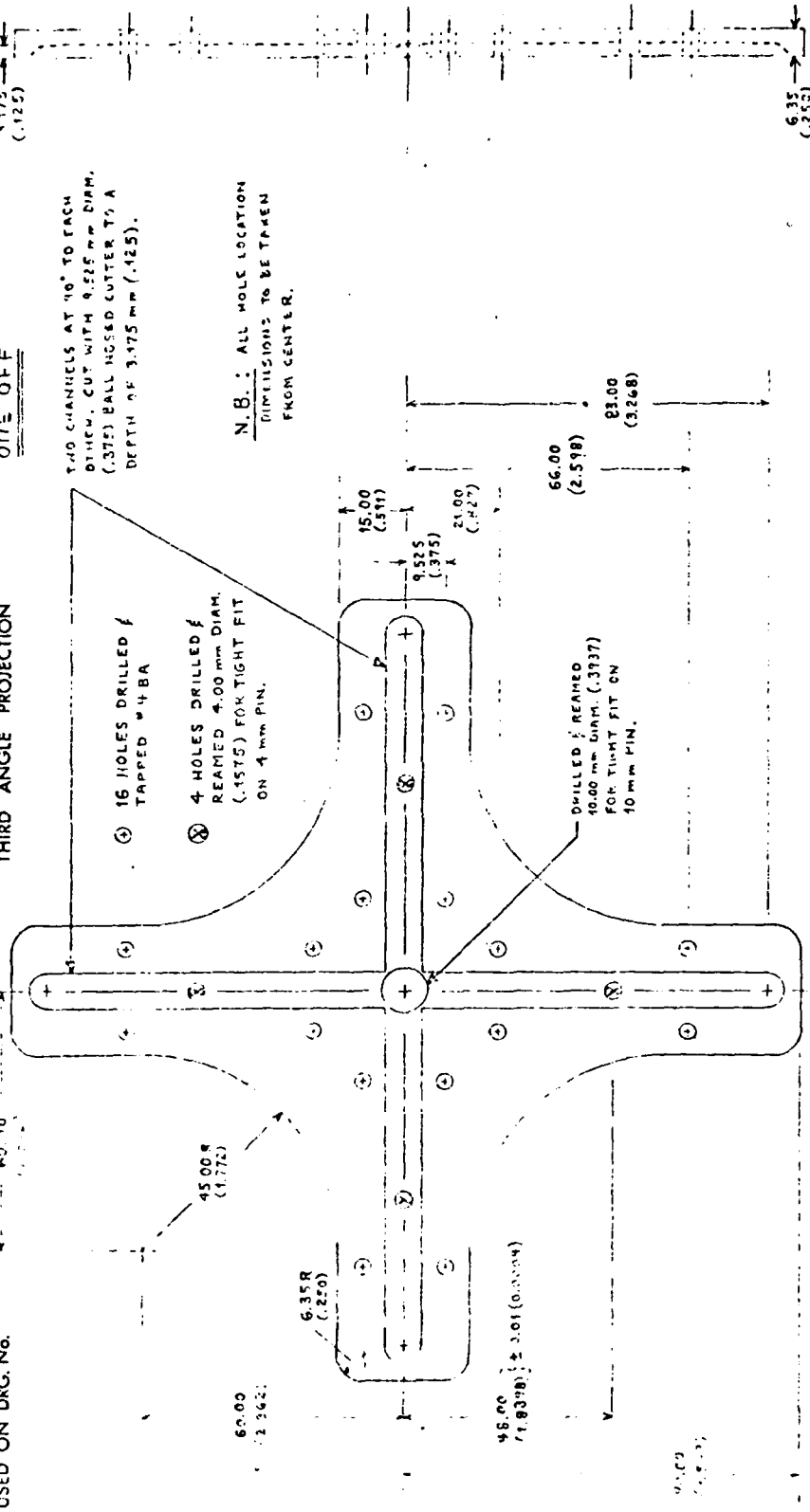
TWO CHANNELS AT 90° TO EACH OTHER, CUT WITH 9.525 mm DIAM. (.375) BALL NOSED CUTTER TO A DEPTH OF 3.175 mm (.125).

N.B.: ALL HOLE LOCATION DIMENSIONS TO BE TAKEN FROM CENTER.

16 HOLES DRILLED & TAPPED #4 BA

4 HOLES DRILLED & REAMED 4.00 mm DIAM. (.1575) FOR TIGHT FIT ON 4 mm PIN.

DRILLED & REAMED 10.00 mm DIAM. (.3937) FOR TIGHT FIT ON 10 mm PIN.



| ISSUE | DATE | MODIFICATION | MATERIALS | DWG. AL | TOLERANCES 0.025 (.001) FOR CHANNELS & PIN HOLES, 0.10 (.004) OTHERWISE. | DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY |
|-------|------|--------------|-----------|----------|--|--|
| | | | FINISH | | | |
| | | | SCALE | DRN. DKM | TRD. | TITLE |
| | | | 1:1 | | CHKD. | ACCELERATION MOUNTING PLATE |
| | | | | | | DRAWING No. |
| | | | | | | A |

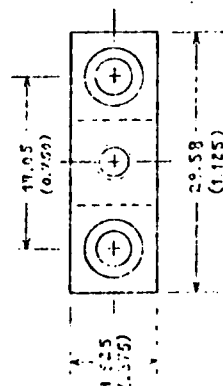
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USED ON DRG. No.

THIRD ANGLE PROJECTION

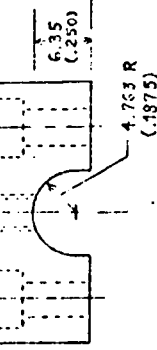
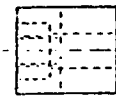
HOLD DOWN BRACKET

EIGHT OFF



DRILL & TAP FOR
#6 BA GRUB SCREW.

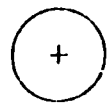
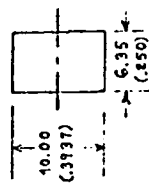
DRILL & COUNTERBORE
TO CLEAR #4 BA CAP
HEAD SCREW.



TO CLAMP 9.525 mm DIAM.
(.375) WITHOUT EXCESSIVE GAP

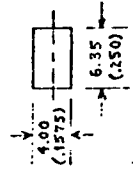
CENTER LOCATING PIN

ONE OFF



OUTER LOCATING PIN

TWELVE OFF



N.B. : TOLERANCE ON BOTH PIN DIAMETERS
IS ± 0.01 mm (0.0004)

| ISSUE | DATE | MODIFICATION | MATERIALS | DURAL | TOLERANCES | 0.05 (0.002) | UNLESS SPECIFIED OTHERWISE | DEPARTMENT OF ENGINEERING SCIENCE | OXFORD UNIVERSITY | TITLE | ACCELEROMETER MOUNTING PLATE HARDWARE | DRAWING No. | 8111/3 |
|-------|------|--------------|-----------|-------|------------|--------------|----------------------------|-----------------------------------|-------------------|-------|---------------------------------------|-------------|--------|
| | | | FINISH | | | | | | | | | | |
| | | | SCALE | 2:1 | DRN. | DKM | TRD. | 24 SEP 70 | CHKD. | | | | |
| | | | | | | | | | | | | | |

Pre-amplifier/Amplifier Specifications



LM121/LM221/LM321 precision preamplifiers

general description

The LM121 series are precision preamplifiers designed to operate with general purpose operational amplifiers to drastically decrease DC errors. Drift, bias current, common mode and supply rejection are more than a factor of 10 better than standard op amps alone. Further, the added DC gain of the LM121 decreases the closed loop gain error.

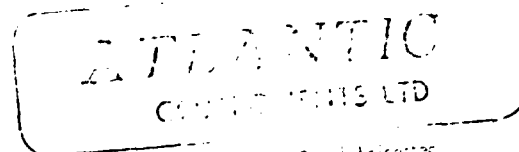
The LM121 operates with supply voltages from $\pm 3V$ to $\pm 20V$ and has sufficient supply rejection to operate from unregulated supplies. The operating current is programmable from $5\mu A$ to $200\mu A$ so bias current, offset current, gain and noise can be optimized for the particular application while still realizing very low drift. Super-gain transistors are used for the input stage so input error currents are lower than conventional amplifiers at the same operating current. Further, the initial offset voltage is easily nulled to zero.

advantages

- Permits optimization of general purpose op amps
- Replaces many specialized op amps

features

- Guaranteed drift less than $1\mu V/^{\circ}C$ when nulled
- Offset voltage less than $0.7 mV$



Atlantic Components Ltd, Leicester
 396 Bath Road, Slough, Berks.
 Tel: 0753 61931 Telex: 341425

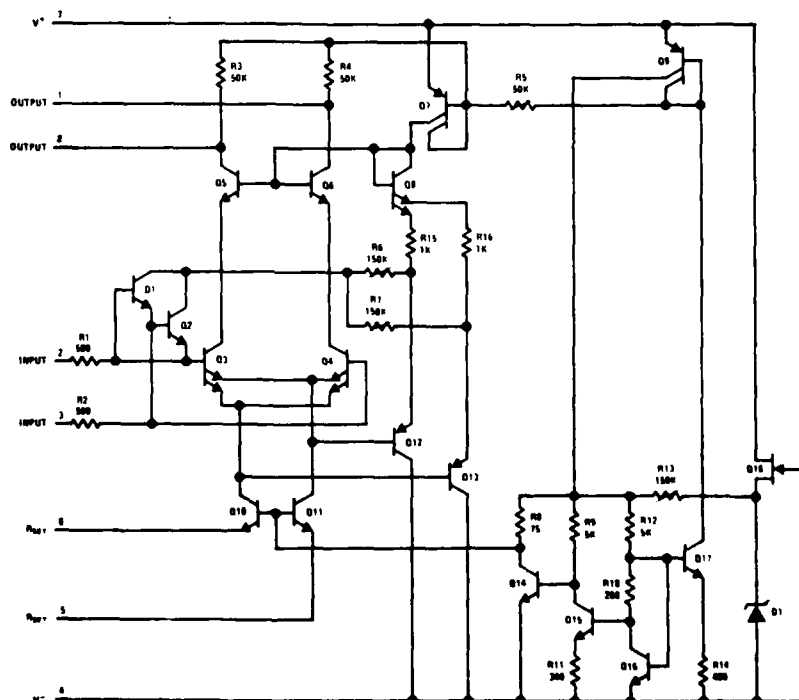
- Bias current less than $50 nA$ at $10\mu A$ operating current
- CMRR 120 dB minimum
- 114 dB supply rejection
- Easily nulled offset voltage

The extremely low drift of the LM121 will improve accuracy on almost any precision DC circuit. For example, instrumentation amplifier, strain gauge amplifiers and thermocouple amplifiers now using chopper amplifiers can be made with the LM121. The full differential input and high common mode rejection are another advantage over choppers. For applications where low bias current is more important than drift, the operating current can be reduced to low values. High operating currents can be used for low voltage noise with low source resistance. The programmable operating current of the LM121 allows tailoring the input characteristics to match those of specialized op amps.

The LM121 is specified over a $-55^{\circ}C$ to $125^{\circ}C$ temperature range, the LM221 over a $-25^{\circ}C$ to $85^{\circ}C$ range and the LM321 over a $0^{\circ}C$ to $70^{\circ}C$ temperature range.

A lower drift version of the LM121 — the LM121A series — is available for applications requiring $0.2\mu V/^{\circ}C$ offset voltage drift.

schematic diagram*



*Pin connections shown on schematic diagram and typical applications are for TO-5 package.

absolute maximum ratings

| | |
|---|----------------|
| Supply Voltage | ±20V |
| Power Dissipation (Note 1) | 500mW |
| Differential Input Voltage (Notes 2, 3) | ±15V |
| Input Voltage (Note 3) | ±15V |
| Operating Temperature Range | |
| LM121 | −55°C to 125°C |
| LM221 | −25°C to 85°C |
| LM321 | 0°C to 70°C |
| Storage Temperature Range | −65°C to 150°C |
| Lead Temperature (Soldering, 10 sec) | 300°C |

electrical characteristics (Note 4)

| PARAMETER | CONDITIONS | LM121 LM221 | LM321 | UNITS | |
|---|---|----------------|-------|------------------------------|-----|
| Input Offset Voltage | $T_A = 25^\circ\text{C}$ $6.4\text{k} \leq R_{\text{Set}} \leq 70\text{k}$ | 0.7 | 1.5 | mV | Max |
| Input Offset Current | $T_A = 25^\circ\text{C}$ $R_{\text{Set}} = 70\text{k}$ | 1 | 2 | nA | Max |
| | $R_{\text{Set}} = 6.4\text{k}$ | 10 | 20 | nA | Max |
| Input Bias Current | $T_A = 25^\circ\text{C}$ $R_{\text{Set}} = 70\text{k}$ | 10 | 18 | nA | Max |
| | $R_{\text{Set}} = 6.4\text{k}$ | 100 | 180 | nA | Max |
| Input Resistance | $T_A = 25^\circ\text{C}$ $R_{\text{Set}} = 70\text{k}$ | 4 | 2 | MΩ | Min |
| | $R_{\text{Set}} = 6.4\text{k}$ | 0.4 | 0.2 | MΩ | Min |
| Supply Current | $T_A = 25^\circ\text{C}$ | 1.5 | 2.2 | mA | Max |
| Input Offset Voltage | $6.4\text{k} \leq R_{\text{Set}} = 70\text{k}$ | 1 | 2.5 | mV | Max |
| Input Bias Current | $R_{\text{Set}} = 70\text{k}$ | 30 | 28 | nA | Max |
| | $R_{\text{Set}} = 6.4\text{k}$ | 300 | 280 | nA | Max |
| Input Offset Current | $R_{\text{Set}} = 70\text{k}$ | 3 | 4 | nA | Max |
| | $R_{\text{Set}} = 6.4\text{k}$ | 30 | 40 | nA | Max |
| Average Temperature Coefficient of Input Offset Voltage | $R_S \leq 200\Omega$ $6.4\text{k} \leq R_{\text{Set}} \leq 70\text{k}$ Offset Voltage Nulled | 1 | 1 | $\mu\text{V}/^\circ\text{C}$ | Max |
| Supply Current | | 2.5 | 3.5 | mA | Max |
| Input Voltage Range | $V_S = \pm 15\text{V}$ $R_{\text{Set}} = 70\text{k}$ | ±13 | ±13 | V | Min |
| | $R_{\text{Set}} = 6.4\text{k}$ (Note 5) | +7 | +7 | V | Min |
| | | −13 | −13 | V | Min |
| Common Mode Rejection Ratio | $R_{\text{Set}} = 70\text{k}$ | 120 | 114 | dB | Min |
| | $R_{\text{Set}} = 6.4\text{k}$ | 114 | 114 | dB | Min |
| Supply Voltage Rejection Ratio | $R_{\text{Set}} = 70\text{k}$ | 120 | 114 | dB | Min |
| | $R_{\text{Set}} = 6.4\text{k}$ | 114 | 114 | dB | Min |
| Voltage Gain | $T_A = 25^\circ\text{C}$ $R_{\text{Set}} = 70\text{k}$ $R_L > 3\text{ meg}$ | 16 | 12 | V/V | Min |

Note 1: The maximum junction temperature of the LM121 is 150°C, while that of the LM221 is 100°C. The maximum junction temperature of the LM321 is 85°C. For operating at elevated temperature, devices in the TO-5 package must be derated based on a thermal resistance of 150°C/W, junction to ambient, or 45°C/W, junction to case. For the flat package, the derating is based on a thermal resistance of 185°C/W when mounted on a 1/6-inch-thick epoxy glass board with ten, 0.03-inch-wide, 2-ounce copper conductors. The thermal resistance of the dual-in-line package is 100°C/W, junction to ambient.

Note 2: The inputs are shunted with back-to-back diodes in series with a 500Ω resistor for overvoltage protection. Therefore, excessive current will flow if a differential input voltage in excess of 1V is applied between the inputs.

Note 3: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

Note 4: These specifications apply for $\pm 5 \leq V_S < \pm 20\text{V}$ and $-55^\circ\text{C} \leq T_A \leq 125^\circ\text{C}$, unless otherwise specified. With the LM221, however, all temperature specifications are limited to $-25^\circ\text{C} \leq T_A \leq 85^\circ\text{C}$, and for the LM321 the specifications apply over a 0°C to 70°C temperature range.

Note 5: External precision resistors—0.1%—can be placed from pins 1 and 8 to 7 to increase positive common mode range.

typical applications

Low Drift Op Amp Using the LM121 as a Preamp

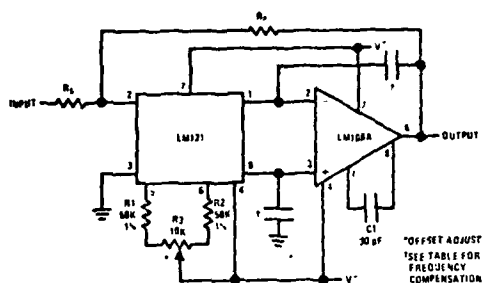


FIGURE 1.

frequency compensation

Universal Frequency Compensation

The additional gain of the LM121 preamplifier when used with an operational amplifier usually necessitates additional frequency compensation. When the closed loop gain of the op amp with the LM121 is less than the gain of the LM121 alone, more compensation is needed. The worst case situation is when there is 100% feedback — such as a voltage follower or integrator — and the gain of the LM121 is high. When high closed loop gains are used — for example $A_V = 1000$ — and only an addition gain of 200 is inserted by the LM121, the frequency compensation of the op amp will usually suffice.

The frequency compensation shown here is designed to operate with any unity-gain stable op amp. Figure 1 shows the basic configuration of frequency stabilizing network. In operation the output of the LM121 is rendered single ended by a $0.01\mu\text{F}$ bypass capacitor to ground. Overall frequency compensation then is achieved by an integrating capacitor around the op amp.

$$\text{Bandwidth at unity gain} \approx \frac{12}{2\pi R_{\text{Set}} C}$$

$$\text{for } 0.5 \text{ MHz bandwidth } C \approx \frac{4}{10^6 R_{\text{Set}}}$$

For use with higher frequency op amps such as the LM118 the bandwidth may be increased to about 2 MHz.

If the closed loop gain is greater than unity "C" may be decreased by

$$C = \frac{4}{10^6 A_{\text{CL}} R_{\text{Set}}}$$

Gain of 1000 Instrumentation Amplifier

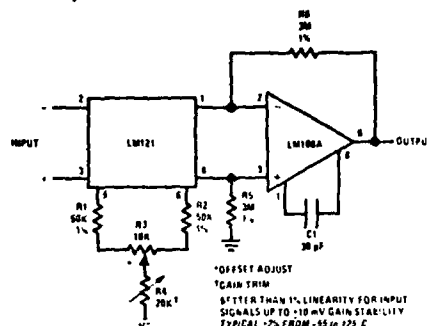


FIGURE 2.

Alternate Compensation

The two compensation capacitors can be made equal for improved power supply rejection. In this case the formula for the compensation capacitor is

$$C \approx \frac{8}{10^6 A_{\text{CL}} R_{\text{Set}}}$$

Table 1 shows typical values for the two compensating capacitors for various gains and operating currents.

TABLE 1.

| CLOSED LOOP GAIN | CURRENT SET RESISTOR | | | | |
|------------------|----------------------|------|------|------|------|
| | 120kΩ | 60kΩ | 30kΩ | 12kΩ | 6kΩ |
| $A_V = 1$ | 68 | 130 | 270 | 680 | 1300 |
| $A_V = 5$ | 15 | 27 | 56 | 130 | 270 |
| $A_V = 10$ | 10 | 15 | 27 | 68 | 130 |
| $A_V = 50$ | 1 | 3 | 5 | 15 | 27 |
| $A_V = 100$ | — | 1 | 3 | 5 | 10 |
| $A_V = 500$ | — | — | 1 | 1 | 3 |
| $A_V = 1000$ | — | — | — | — | — |

This table applies for the LM108, LM101A, LM741, LM118. Capacitance is in pF.

Design equations for the LM121 series:

$$\text{Gain } A_V \approx \frac{1.2 \times 10^6}{R_{\text{Set}}}$$

Null Pot Value should be 10% of R_{Set}

$$\text{Operating Current} \approx \frac{2 \times 0.65\text{V}}{R_{\text{Set}}}$$

$$\text{Positive Common Mode Limit} \approx V^+ - 0.6 + \frac{0.65\text{V} \times 50\text{k}}{R_{\text{Set}}}$$

definition of terms

Input Offset Voltage: That voltage which must be applied between the input terminals through two equal resistances to obtain zero output voltage.

Input Offset Current: The difference in the currents into the two input terminals when the output is at zero.

Input Voltage Range: The range of voltages on the input terminals for which the offset specifications apply.

Input Bias Current: The average of the two input currents.

Common Mode Rejection Ratio: The ratio of the

input voltage range to the peak-to-peak change in input offset voltage over this range.

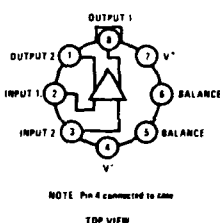
Supply Current: The current required from the power supply to operate the amplifier.

Voltage Gain: The ratio of the differential output voltage swing to the change in input voltage required to drive the output from zero to this voltage.

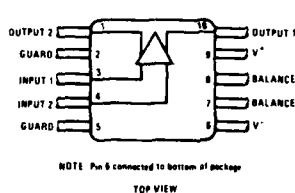
Power Supply Rejection: The ratio of the change in input offset voltage to the change in power supply voltages producing it.

connection diagrams

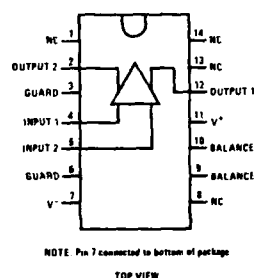
Metal Can



Flat Package

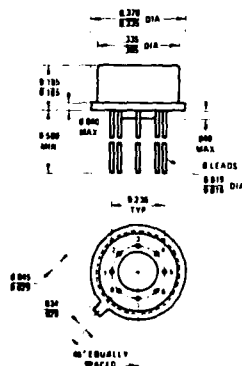


Dual-In-Line

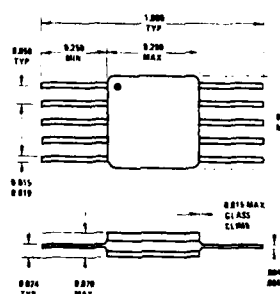


Note: Outputs are inverting from the input of the same number.

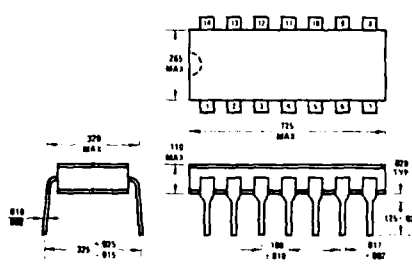
physical dimensions



Order Numbers:
LM121H, LM221H, LM321H



Order Numbers:
LM121F, LM221F, LM321F



Order Numbers:
LM121D, LM221D, LM321D

Manufactured under one or more of the following U.S. patents: 3083262, 3189758, 3231797, 3303356, 3317671, 3323071, 3381071, 3408542, 3421025, 3426423, 3440498, 3518750, 3519857, 3557431, 3560765, 3566718, 3571810, 3575609, 3579059, 3593069, 3597640, 3607469, 3617859, 3631312, 3633052, 3638131, 3648071, 3651565, 3693248

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National Semiconductor (UK) Ltd.
Larkfield Industrial Estate, Greenock, Scotland. Tele 33251/Telex 778-632



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Operational Amplifiers

LM108A/LM208A/LM308A operational amplifier general description

The LM108A, LM208A and LM308A are precision operational amplifiers having specifications about a factor of ten better than FET amplifiers over their operating temperature range. In addition to low input currents, these devices have extremely low offset voltage, making it possible to eliminate offset adjustments, in most cases, and obtain performance approaching chopper stabilized amplifiers.

The devices operate with supply voltages from +2V to +20V and have sufficient supply rejection to use unregulated supplies. Although the circuit is interchangeable with and uses the same compensation as the LM101A, an alternate compensation scheme can be used to make it particularly insensitive to power supply noise and to make supply bypass capacitors unnecessary. Outstanding characteristics include:

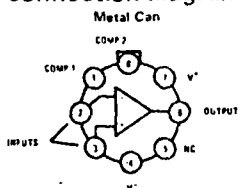
- Offset voltage guaranteed less than 0.5 mV
- Maximum input bias current of 3.0 nA over temperature

- Offset current less than 400 pA over temperature
- Supply current of only 300 μ A, even in saturation
- Guaranteed 5 μ V/ $^{\circ}$ C drift.

The low current error of the LM108A series makes possible many designs that are not practical with conventional amplifiers. In fact, it operates from 10 M Ω source resistances, introducing less error than devices like the 709 with 10 k Ω sources. Integrators with drifts less than 500 μ V/sec and analog time delays in excess of one hour can be made using capacitors no larger than 1 μ F.

The LM208A is identical to the LM108A, except that the LM208A has its performance guaranteed over a -25° C to 85° C temperature range, instead of -55° C to 125° C. The LM308A has slightly-relaxed specifications and has its performance guaranteed over a 0° C to 70° C temperature range.

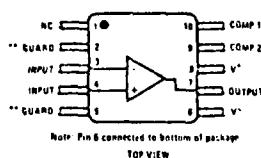
connection diagrams *



Note: Pin 8 connected to case
*Pin connections shown on schematic diagram are for TO-5 package
**Guard pin (pin 10) is connected to ground for input anti-leakage guarding on printed circuit boards.

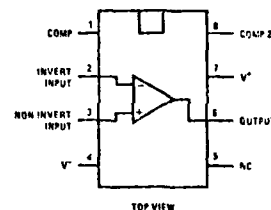
Order Number LM108AH or
LM208AH or LM308AH
See Package 11

Flat Package



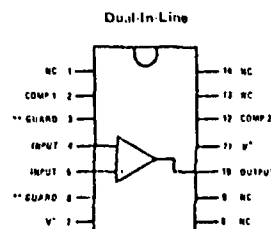
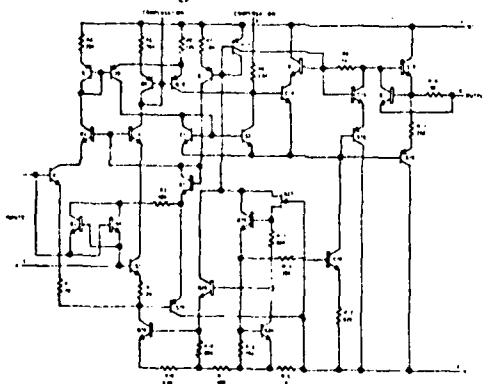
Order Number LM108AF or
LM208AF or LM308AF
See Package 3

Dual-In-Line



Order Number LM308AN
See Package 20

schematic diagram *



Note: Pin 7 connected to bottom of package
TOP VIEW

Order Number LM108AD
or LM208AD or LM308AD
See Package 1



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London EC2P 2HA

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DATA SHEET

DUAL REGULATORS

FIXED ± 15 VOLT

305-636

VARIABLE ± 0.05 TO ± 30 VOLT

306-011

Two monolithic regulators in D.I.L. packages giving fixed or variable complementary outputs. Currents to 100mA. Internal current limiting and thermal shutdown.

FEATURES

TYPE

Fixed 305-636

 V_{IN} ± 18 to ± 30 V I_o

100mA

 P_{tot}

600mW

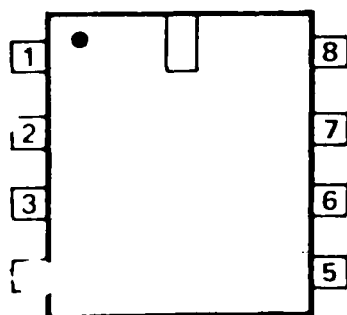
Variable 306-011

 ± 9.5 to ± 35 V

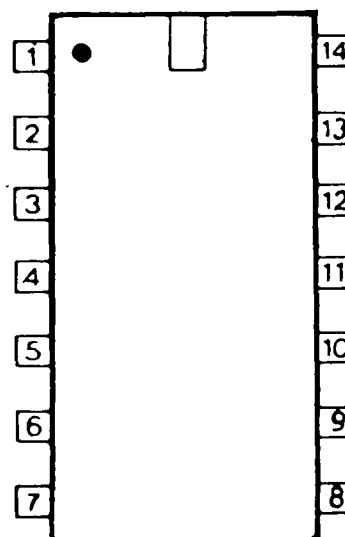
100mA

900mW

CONNECTIONS



1. + COMPENSATION
2. GROUND
3. - COMPENSATION
4. - V_{IN}
5. - 15V OUTPUT
6. BALANCE
7. + 15V OUTPUT
8. + V_{IN}



1. + V OUTPUT
2. N.C.
3. - COMPENSATION
4. BALANCE
5. + COMPENSATION
6. N.C.
7. - V_{IN}
8. - V_{OUT}
9. N.C.
10. R_{ADJ}
11. R_{CAL}
12. GND
13. N.C.
14. + V_{IN}

ALL CONNECTIONS VIEWED FROM THE TOP.

ABSOLUTE MAXIMUM RATINGS AT $T_{AMB} 25^{\circ}\text{C}$

Input voltage ± 30
 P_{tot} 600
 T_J (thermal protected) ± 175

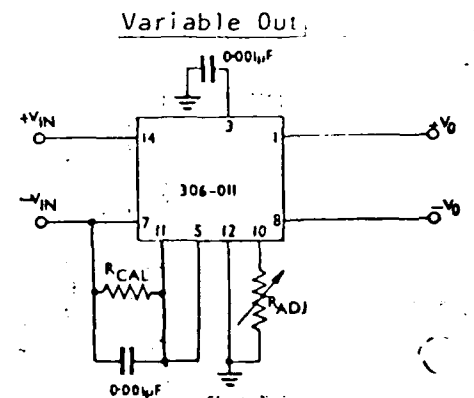
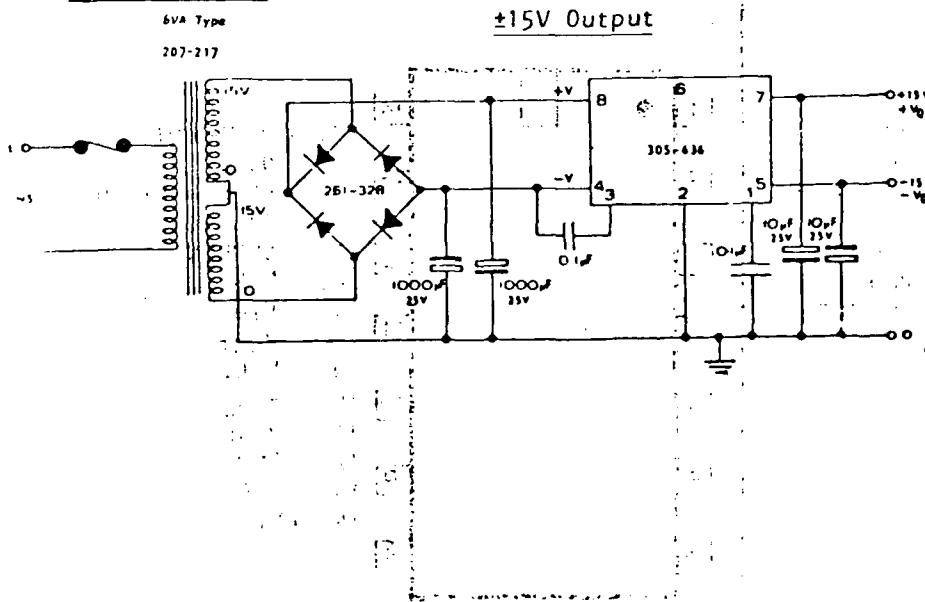
± 35 V
 900 mW
 ± 175 $^{\circ}\text{C}$

ELECTRICAL CHARACTERISTICS

(at $T_J = 25^{\circ}\text{C}$, $V_{IN} \pm 20\text{V}$, $C_O = 10\mu\text{F}$, $I_O = \pm 1\text{mA}$; unless otherwise stated).

| | | 1,305 - 636 | | | 306 - 011 | | | | |
|--------------------------------------|------------------------|-------------|-----------|-----------|------------|-----------|-----|-----------------------|---|
| PARAMETER | | MIN | TYP | MAX | MIN | TYP | MAX | UNIT | |
| V_{out} | (positive to negative) | 14.5 | 15.0 | 15.5 | Adjustable | 0.05 | - | 30 | V |
| V_{IN} | " " | 18 | - | 30 | 9.5 | - | 35 | V | |
| INPUT/OUTPUT DIFF. VOLTAGE @ 50mA | | 3 | - | - | 3 | - | - | - | |
| OUTPUT VOLTAGE BALANCE | | - | ± 0.3 | ± 1.8 | - | ± 1.5 | - | % V_{out} | |
| LINE REGULATION | | - | 0.01 | 0.1 | - | 0.02 | 0.2 | % V_{out} | |
| LOAD REGULATION (to 100mA) | | - | 0.03 | 0.2 | - | 0.1 | 0.4 | % V_{out} | |
| RIPPLE REJECTION | | - | 75 | - | - | 70 | - | dB | |
| OUTPUT VOLTAGE TEMP. COEFF. | | - | 0.005 | 0.005 | - | 0.015 | - | %/ $^{\circ}\text{C}$ | |
| SHORT CIRCUIT CURRENT (SET INTERNAL) | | - | 220 | - | - | 300 | - | mA | |
| STAND BY CURRENT $\pm I_o = 0$ | | - | 1.5 | 3.0 | - | 1.2 | 3.0 | mA | |
| OUTPUT NOISE VOLTAGE 100 Hz - 10kHz | | - | 60 | - | - | 250 | - | $\mu\text{V rms}$ | |
| INTERNAL SHUTDOWN TEMP. | | - | 175 | - | - | 175 | - | $^{\circ}\text{C}$ | |

BASIC CIRCUIT



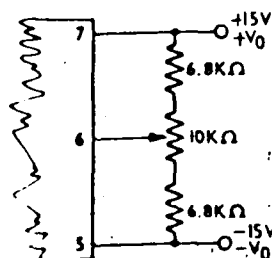
$$R_{CAL} = 72\text{k}\Omega$$

$$(120\text{k}\Omega + 180\text{k}\Omega \text{ in parallel} = 72\text{k}\Omega)$$

$$R_{ADJ} = 2.5\text{k}\Omega \text{ per Volt output.}$$

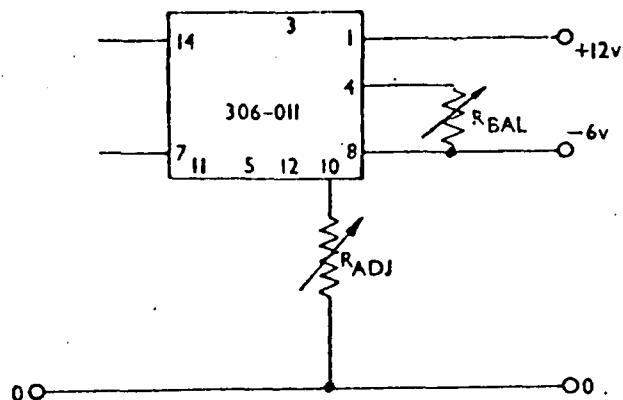
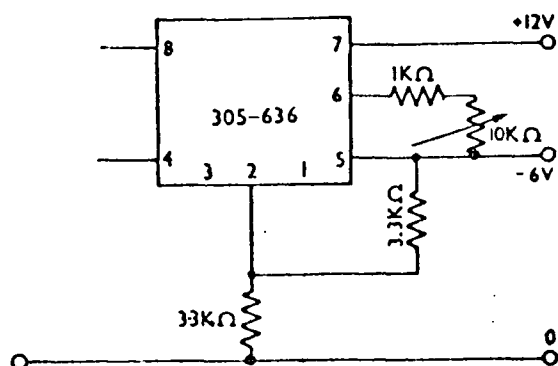
$$(\text{For } \pm 15\text{V use } 50\text{k}\Omega \text{ lin. pot})$$

To balance fixed regulator additional potentiometer circuit can be used.



Modification to circuits to obtain non-symmetrical outputs.

Requirement typically for 710 type comparators are +12 and -6 Volts.



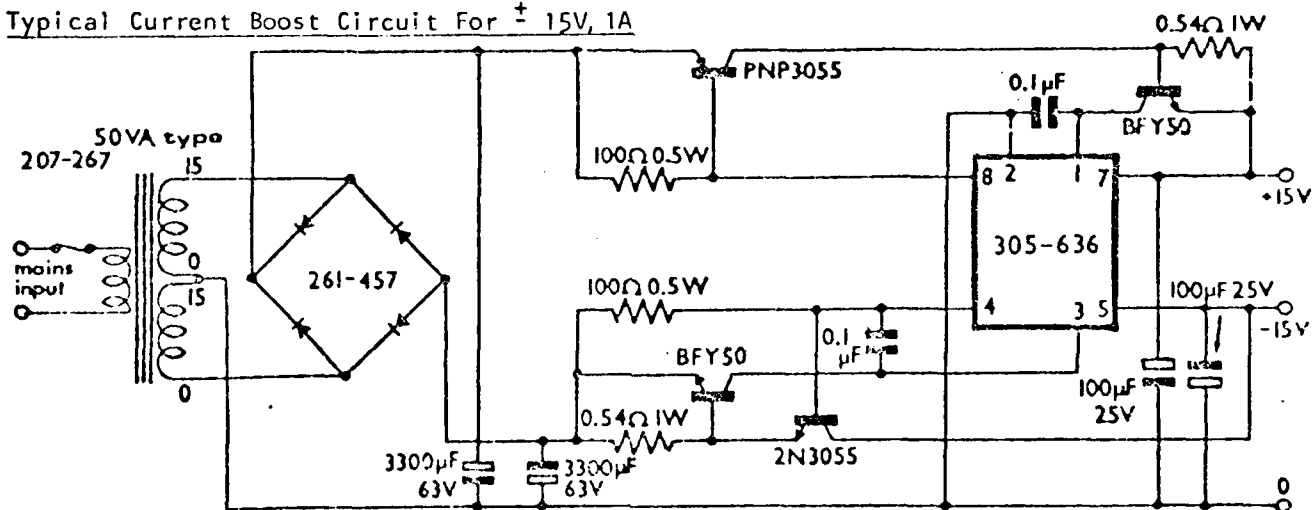
$$R_{CAL} = 72k\Omega$$

$$R_{ADJ} = 2.5k\Omega \text{ per Volt of output}$$

$$R_{ADJ} \text{ for } -6V = 15k\Omega, \text{ then}$$

$$R_{BAL} \text{ for } +12V = 20k\Omega$$

Typical Current Boost Circuit For $\pm 15V, 1A$



Performance at $20^{\circ}C T_{amb}$

$$I_o = \pm 1A$$

$$\text{Load reg. (0-1A)} = 1.1\%$$

$$\text{Ripple rejection} = 60dB$$

$$\text{Line reg. (18-30V)} = 0.065\%$$

$$\text{Current limit } \pm 1.02A$$

Heatsink for each 3055 transistor $4^{\circ}C/W$ (401-497)
0.54Ω limit resistors are $2 \times 0.27\Omega \frac{1}{2}W$ in series.

Data Processing Computer Program Listings

```

C***      PROGRAM CALIB1
C***THIS PROGRAM READS 16 CHANNELS OF DATA FOR EACH OF
C*** 6 POSITIONS, CONVERTS IT TO REAL VOLTAGES, AND OUTPUTS
C*** THE RESULTS IN A TABLE OF THE FORM:
C***      POS  CHAN1  CHAN2  CHAN3.....CHAN16
C***IT ALSO OUTPUTS SCALE FACTORS AND OFFSETS FOR THESE CHANNELS
C***AND STORES THESE IN DISC FILE DKO:CALIBD.DAT.
C***
C***      LINK AS CALIB1=CALIB1,ADCSET,ASCAN,SYSLIB/F
C***
      DIMENSION ICTLWD(16),JPOL(16),IREAD(16),TABL(6,16),
1      ITIT(3),OUTABL(4,16),ITIM(4),ITIME(12),SCALF(48),
2      OFFSET(48),STORE(5,16)
      LOGICAL*1 IDAT(9),IDATE(9)
      DATA IYES/'YE'/,IBE1/'BE'/,IBE2/'FO'/,IBE3/'RE'/
      DATA IAF1/'A'/,IAF2/'FT'/,IAF3/'ER'/,IAFT/'AF'/
      COMMON /ASV/IF25
      IOB=7
      IKB=5
      CALL ASSIGN(9,'KB:',0,)
      IOD=9
      JPOS=6
      NCHAN=16
C***ENTER SUBJECT AND RECORD NUMBER
      WRITE(IOB,2000)
2000      FORMAT(10X,'ENTER RECORD NUMBER AND SUBJECT NUMBER')
      READ(IKB,1000) IREC,ISUB
1000      FORMAT(2I4)
C***SET BEFORE OR AFTER WALK CALIBRATION FLAG
      WRITE(IOB,2010)
2010      FORMAT(10X,'IS THIS BEFORE WALK CALIBRATION?(YES/NO)')
      READ(IKB,1010) IY
1010      FORMAT(A2)
      ITIT(1)=IBE1
      ITIT(2)=IBE2
      ITIT(3)=IBE3
      IF(IY.EQ.1YES) GO TO 5
      ITIT(1)=IAF1
      ITIT(2)=IAF2
      ITIT(3)=IAF3
5          CALL DATE(IDAT)
          CALL TIME(ITIM)
C***SET 16 CHANNELS TO RIPOLAR MODE
      DO 10 J=1,16
10          IPOL(J)=2
C***ZERO TABL ARRAY
      DO 20 J=1,6
      DO 20 N=1,16
20          TABL(J,N)=0.0
C***SET UP ADC WORDS
      CALL ADCSET(NCHAN,IPOL,ICTLWD)
C***TAKE CALIBRATION DATA FOR JPOS POSITIONS
      DO 70 J=1,JPOS
      PAUSE 'CR TO TAKE DATA SAMPLE'
C***TAKE 5 SAMPLES FOR EACH CHANNEL, CONVERT TO REAL VOLTAGES
      DO 30 I=1,5
      CALL ASCAN(NCHAN,ICTLWD,IREAD)
      DO 30 K=1,NCHAN
30          STORE(I,K)=(FLOAT(IREAD(K)-512*(IPOL(K)-1)))/204.8048
C***TAKE THE MEAN AND STORE IN TABL ARRAY
      DO 40 I=1,5
      DO 40 K=1,NCHAN
40          TABL(J,K)=TABL(J,K)+STORE(I,K)

```

```

      DO 50 K=1,NCHAN
      SAMPS=5.0
      TABL(J,K)=TABL(J,K)/5.0
C***ELIMINATE SAMPLES .GT. + OR - 10 MV-S FROM MEAN
      DO 50 J=1,5
      IF(STORE(I,K).GT.+0.01).OR.STORE(I,K).LT.(TABL(J,K)
1      (TABL(J,K)-.01)) TABL(J,K)=(5.0*TABL(J,K)-STORE(I,K))
2      /((SAMPS-1.0))
50      CONTINUE
70      CONTINUE
C***WRITE HEADING AND VOLTAGE READING TABLE TO PRINTER
      WRITE(IOD,2020) ITIT,ISUB,IREF,(ITAT(1),I=1,9),ITIM
2020      FORMAT(1H,/,3A2,' WALK CALIBRATION FOR SUBJECT NUMBER: ',
1      I4,5X,'RECORD NUMBER:',I4,5X,'DATE: ',9A1,5X,'TIME: ',4A2)
      WRITE(IOD,2060)
2060      FORMAT(1H, 'CALIBRATION DATA TABLE (IN VOLTS)')
      WRITE(IOD,2080) (J,J=1,16)
2080      FORMAT(16(6X,I2))
      WRITE(IOD,2090) (J,(TABL(J,K),K=1,NCHAN),J=1,JPOS)
2090      FORMAT(12,16F8.3)
C***COMPUTE SCALE FACTORS (IN VOLTS/G)
C***      FOR INDIVIDUAL ACCELEROMETER CHANNELS
      OUTABL(1,1)=(TABL(2,1)-TABL(4,1))*0.5
      OUTABL(1,2)=(TABL(2,2)-TABL(4,2))*0.5
      DO 80 M=3,6
80      OUTABL(1,M)=(TABL(5,M)-TABL(6,M))*0.5
      OUTABL(1,7)=(TABL(3,7)-TABL(1,7))*0.5
      OUTABL(1,8)=(TABL(3,8)-TABL(1,8))*0.5
C***COMPUTE SCALE FACTORS (IN VOLTS/G) FOR
C***      DIFFERENCE AMPLIFIER CHANNELS
      OUTABL(1,9)=(OUTABL(1,1)+OUTABL(1,2))*3.0*0.5
      OUTABL(1,10)=(OUTABL(1,3)+OUTABL(1,4))*4.74*0.5
      OUTABL(1,11)=(OUTABL(1,5)+OUTABL(1,6))*4.74*0.5
      OUTABL(1,12)=(OUTABL(1,7)+OUTABL(1,8))*3.0*0.5
C***COMPUTE SCALE FACTORS (IN VOLTS/G) FOR SUMMING
C***      AMPLIFIER CHANNELS.
      OUTABL(1,13)=(TABL(2,13)-TABL(4,13))*0.25
      OUTABL(1,14)=(TABL(5,14)-TABL(6,14))*0.25
      OUTABL(1,15)=(TABL(5,15)-TABL(6,15))*0.25
      OUTABL(1,16)=(TABL(3,16)-TABL(1,16))*0.25
C***COMPUTE OFFSETS (IN VOLTS) FOR ALL CHANNELS
      DO 90 M=1,6
90      OUTABL(2,M)=TABL(1,M)
      OUTABL(2,7)=(TABL(3,7)+TABL(1,7))*0.5
      OUTABL(2,8)=(TABL(3,8)+TABL(1,8))*0.5
      DO 100 M=9,15
100      OUTABL(2,M)=TABL(1,M)
      OUTABL(2,16)=(TABL(3,16)+TABL(1,16))*0.5
      WRITE(IOD,2100)
2100      FORMAT(1H, 'CHANNEL',2(10X,'SCALE FACTOR',10X,'OFFSET'))
      WRITE(IOD,2110)
2110      FORMAT(1H,18X,'(VOLTS/G)',11X,'(VOLTS)',10X,'(G-S/VOLT)'
1      ,12X,'(G-S)')
      DO 120 M=1,16
      OUTABL(3,M)=1.0/OUTABL(1,M)
120      OUTABL(4,M)=OUTABL(2,M)/OUTABL(1,M)
      WRITE(IOD,2120) (M,(OUTABL(L,M),L=1,4),M=1,16)
2120      FORMAT(1H,2X,I2,11X,F11.4,8X,F11.4,10X,F11.7,8X,F11.7)
C***STORE SCALE FACTORS AND OFFSETS IN DISC FILE
      ICODE=JAFT
      IF(IY.EQ.IYES) ICODE=IBE1
C***ASSIGN AND DEFINE OUTPUT FILE
      CALL ASSIGN(25,'DK0:CALIBD.DAT',14,'OLD')
      DEFINE FILE 25(10,215,U,IF25)
      DO 190 I=1,9

```

```

      IF(ICODE.EQ.IAFT) GO TO 250
C***IF BEFORE WALK CALIBRATION STORE ONLY INITIAL VALUES
      DO 200 I=1,4
200      ITIME(I)=ITIM(I)
      DO 210 I=5,12
210      ITIME(I)=0
      DO 220 I=1,16
      SCALF(I)=OUTABL(3,I)
220      OFFSET(I)=OUTABL(4,I)
C***FILL REMAINDER WITH ZERO
      DO 230 I=17,48
      SCALF(I)=0.0
230      OFFSET(I)=0.0
      GO TO 300
C***IF AFTER WALK, COMPUTE MEAN OF BEFORE/AFTER WALK; STORE ALL VALUES
C*** FIRST READ BEFORE WALK VALUES
250      READ(25'IREC) IRECST,ISUB,IDATE,ITIME,SCALF,OFFSET
C***INSURE THAT CURRENT AND STORED RECORD NUMBERS ARE THE SAME
      IF(IREC.NE.IRECST) CALL CLOSE(25)
      IF(IREC.NE.IRECST) STOP 'RECORD NUMBERS DO NOT MATCH'
C***STORE AFTER/MEAN WALK TIMES--MEAN = AFTER
      DO 260 I=1,4
      ITIME(I+4)=ITIM(I)
260      ITIME(I+8)=ITIM(I)
C***STORE SCALE FACTORS AND OFFSETS
      DO 270 I=1,16
      SCALF(I+16)=OUTABL(3,I)
270      OFFSET(I+16)=OUTABL(4,I)
C***COMPUTE MEAN VALUES
      DO 280 I=1,16
      SCALF(I+32)=(SCALF(I)+SCALF(I+16))*0.5
280      OFFSET(I+32)=(OFFSET(I)+OFFSET(I+16))*0.5
C***WRITE VALUES TO DISC FILE
300      WRITE(25'IRFC) IREC,ISUB,IDATE,ITIME,SCALF,OFFSET
C***WRITE MEAN VALUES TO PRINTER IF ON AFTER WALK CALIBRATION
      IF(IY.EQ.IYES) GO TO 320
      READ(25'IREC) IREC,ISUB,IDATE,ITIME,SCALF,OFFSET
      WRITE(100,2500) IREC,ISUB,IDATE
2500      FORMAT(1H,2X,'MEAN SCALE FACTORS AND OFFSETS FOR RECORD:'I4,
1          ' SUBJECT: ',I4,' DATE: ',9A1)
      WRITE(100,2520) (SCALF(I),I=33,48)
      WRITE(100,2520) (OFFSET(I),I=33,48)
2520      FORMAT(8(2X,F11.7))
C***CLOSE ALL OPEN FILES
320      CALL CLOSE(25)
      CALL EXIT
      END

```

```

C*** DATLRG ***
C*** PROGRAMME TO READ DATA FROM ADC AND STORE IT ON DISC
C*** WHILE SIMULTANEOUSLY DISPLAYING IT
C***
C*** INITIALISATION
      INTEGER*2 DBLK(4)
      DIMENSION ILIST(3)
      COMMON /ADC/NNT,NCHAN,ICTLWD(16),IPOL(16)
      COMMON /WPARAM/ICHAN,JBLK,IBUFF,ICOUNT,ICTRN
C*** PRESET VALUES
      DATA DBLK/3RDK3,3RADC,3R    ,3RDAT/
      DATA IYES/'YE'/
      DATA ILIST/'170404,0,0'/
C*** INPUT AND OUTPUT CHANNELS
      INP=5
      IOP=7
      CALL SWPR
C*** DEFINE DATA FILE FOR INDEX USE
      CALL ASSIGN(20,'DK3:ADC.DAT',11,'OLD')
      DEFINE FILE20(20,166,U,IF1)
C*** GET RT-11 CHANNEL NUMBER
      ICHAN=IGETC()
      IF (ICHAN.LT.0) STOP 'DATIN CANT ALLOCATE A CHANNEL'
      JCHAN=ICHAN
C*** LOOK UP FILE
      IF(LOOKUP(ICHAN,DBLK).LT.0)STOP 'OPEN ERROR'
C*** FIND NEXT AVAILABLE RECORD
      DO 10 I=1,20
      II=I
      READ(20'II')NNT
      IF(NNT.EQ.0)GOTO 20
10  CONTINUE
C*** ALL RECORDS USED
C*** PROMPT 1
      CALL PRINT('NO UNUSED RECORDS')
      GOTO 30
      *** FIND DETAILS OF LAST ENTRY
      20 IF(I.EQ.1)GOTO 31
      READ(20'I-1')NNT,JBLK,LBLK
      NFBLK=820-LBLK
C*** PROMPT 2
      WRITE(IOP,2000)I,NFBLK
      2000 FORMAT('$NEXT FREE RECORD ',I4,'  NUMBER OF FREE BLOCKS ',
1  16,/1H0)
C*** CHOOSE STARTING RECORD
C*** PROMPT 3
      30 CALL PRINT('DESIRED STAFING RECORD ?')
C*** REPLY
      READ(INP,1000)IREC
C*** ZERO ENTRY CAUSES EXIT
      IF(IREC.EQ.0)GOTO 120
      IF(IREC.NE.1)GOTO 40
C*** SET IREC TO FIRST RECORD IF NONE YET USED
      31 IREC=1
      CALL PRINT('FIRST RECORD')
      NFBLK=806
      CALL FILSET(NFBLK)
      NBLK=NFBLK+1
      LBLK=820-NBLK
      GOTO 45
      40 CONTINUE
C*** IS DESIRED RECORD NON SEQUENTIAL ?

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      IF(IREC.GT.1)CALL PRINT('SEQUENTIAL RECORD SELECTED INSTEAD')
      IF(IREC.GT.1)IREC=1
C*** IS DESIRED RECORD DIFFERENT FROM NEXT FREE RECORD ?
      IF(IREC.EQ.1)GOTO 50
C*** FIND NUMBER OF FREE BLOCKS LEFT FOR DATA
      READ(20'IREC-1)NNT,JBLK,LBLK
      NFBLK=820-LBLK
      NBLK=NFBLK
      45 WRITE(IOP,2010)NBLK
      2010 FORMAT('NUMBER OF FREE BLOCKS ',I6,/1H0)
      50 CONTINUE
      JBLK=LBLK
C***SET FIRST NUMBER TO ZERO IN ALL RECORDS GREATER THAN CHOSEN
C***  RECORD
      NNT=0
      DO 60 J=IREC,20
      JJ=J
      WRITE(20'JJ)NNT
      60 CONTINUE
C*** START PARAMETER ENTRY LOOP
      70 CONTINUE
C*** PROMPT 4
      CALL PRINT('NUMBER OF CHANNELS,SAMPLE TIME(MS),RUN TIME(S)')
C*** REPLY
      READ(INP,1010)NCHAN,TSAMP,TRUN
C*** TRY AGAIN IF TSAMP TOO GREAT
      IF(TSAMP.GT.1280.0)CALL PRINT('SAMPLE RATE>1.28 SEC. MAXIMUM')
      IF(TSAMP.GT.1280.0)GO TO 70
C*** CALCULATE CLOCK RATE
      CALL SHUFFL(TSAMP,NCOUNT,ITEN)
C*** CHANNEL POLARITY SETTING
C*** PROMPT 5
      CALL PRINT('ALL CHANNELS SAME POLARITY (YES/NO) ?')
C*** REPLY
      READ(INP,1020)IY
C*** BRANCH IF ALL SAME POLARITY
      IF(IY.EQ.IYES)GOTO 80
C*** PROMPT 6
      CALL PRINT('ENTER POLARITY VALUE FOR EACH CHANNEL')
      CALL PRINT('(1=UNI,2=BI)')
C*** REPLY
      READ(INP,1030)(IPOL(I),I=1,NCHAN)
      GOTO 100
C*** SET ALL CHANNELS TO SAME POLARITY
C*** PROMPT 7
      80 CALL PRINT('ENTER ONE POLARITY VALUE TO BE ASSIGNED TO')
      CALL PRINT('ALL CHANNELS (1=UNI,2=BI)')
C*** REPLY
      READ(INP,1040)IPOM
      DO 90 I=1,NCHAN
      90 IPOL(I)=IPOM
      100 CONTINUE
C*** CALCULATE NUMBER OF SAMPLES
      NNT=1+IFIX((TRUN*1000.0)/TSAMP)
      101 NNT=NNT
      NFBLK=JBLK+1
C*** SET UP ADC CONTROL WORDS
      CALL ADCSET(NCHAN,IPOL,ICTLWD)
C*** SET UP LIST TO STOP CLOCK INTERRUPT IF RUN ABORTED
      CALL DEVICE(ILIST)
C*** START CLOCK
      CALL CLKSET(NCOUNT,ITEN)
C*** PAUSE READY TO START
C*** PROMPT 8
      WRITE(IOP,2020)IREC

```



```
      PAUSE 'CR TO START'
      CALL ADCCTL
      ANT=MNT-NNT
      WRITE(20,IREC)NNT,NFBLK,JBLK,NCOUNT,ITEN,NCHAN,IPOL
C*** INCREMENT RECORD NUMBER
      IREC=IREC+1
C*** EXIT IF ALL RECORDS ARE USED UP
      IF(IREC.GT.20)GOTO 110
      NFBLK=JBLK
C*** BLOCKS LEFT
C*** PROMPT 9
      WRITE(10P,2030)820-JBLK
      2030 FORMAT('NUMBER OF FREE BLOCKS LEFT= ',I6,/1H0)
C*** OPTION TO EXIT
C*** PROMPT 10
      CALL PRINT('EXIT FROM DATIN (YES/NO) ?')
C*** REPLY
      READ(INP,1020)IY
      IF(IY.EQ.IYES)GOTO 120
C*** OPTION TO ALTER PARAMETERS IN NEXT RECORD
C*** PROMPT 11
      CALL PRINT('ALTER CONVERSION PARAMETERS (YES/NO) ?')
C*** REPLY
      READ(INP,1020)IY
      IF(IY.EQ.IYES)GOTO 70
      GOTO 101
C*** PROMPT 12
      110 CALL PRINT('ALL RECORDS USED')
      120 CALL CLOSEC(JCHAN)
      CALL IFREEC(JCHAN)
      STOP
1000 FORMAT(I4)
1010 FORMAT(I8,2F10.4)
1020 FORMAT(A2)
1030 FORMAT(16I3)
1040 FORMAT(I3)
      END
```


[illegible]


```

C***      PROGRAM STRDAT
C***  THIS PROGRAM RECOVERS DATA STORED IN ADC.DAT BY DATIN AND
C***STORES IT IN INTEGER FORM IN DISC FILE DK0:RAWACC.DAT LOCATED ON
C***DISC S.A.D. THE INDEX TO THIS DATA IS STORED BY RECORD NUMBER IN
C***BLOCKS 1-50 OF RAWACC.DAT.
      DIMENSION IPOL(16),ENDS(2,20),SCALF(16),OFSET(16),IDATA(256)
      DIMENSION IPOLB(16),SCALFB(16),OFSETB(16)
      DIMENSION JSBLK(42),JFBLK(42),JFWRD(42),NSAMP(42)
      DIMENSION JSBLKB(42),JFBLKB(42),JFWPDB(42),NSAMPB(42)
      COMMON /ASV/IF10,IF11,IF40
      DATA IYES/'YE'/
      IKB=5
      IOD=7
      ISECS=1
      CALL ASSIGN(8,'KB:',0,)
C***ENTER INPUT RECORD AND NUMBER OF CHANNELS
      WRITE(IOD,2030)
      READ(IKB,1000) IR,NCHAN
C***READ INDEX FILE
      CALL ASSIGN(10,'DK3:ADC.DAT',11,'OLD')
      DEFINE FILE 10(20,166,U,IF10)
      READ(10'IR) NNT,INBLK,ILST,NCOUNT,ITEN,MCHAN,IPOL,ENDS,
1          SCALF,OFSET
      REWIND 10
      CALL CLOSE(10)
C***TEST FOR WRONG NUMBER OF CHANNELS
      IF(MCHAN.NE.NCHAN) STOP 'WRONG NUMBER OF CHANNELS'
C***TEST FOR EMPTY RECORD
      IF(NNT.EQ.0) STOP 'EMPTY RECORD'
C***ENTER SUBJECT NUMBER, HOSPITAL NUMBER AND TEST NUMBER
      WRITE(IOD,2040)
      READ(IKB,1000) ISUBN,IHOSN
      WRITE(IOD,2050)
      READ(IKB,1010) ITSTN
C***OPEN OUTPUT FILE AND TEST IF ANY DATA PREVIOUSLY STORED ON DK0
      CALL ASSIGN(11,'DK0:RAWACC.DAT',14,'OLD')
      DEFINE FILE 11(2050,256,U,IF11)
      READ(11'1) IRT
      IF(IRT.LT.0) IRT=-IRT
      IF(IRT.EQ.1) GO TO 10
C***IF NO DATA PREVIOUSLY STORED ON DK0,SET VARIABLES FOR RECORD 1
      IRB=0          !RESULTS IN OUTPUT RECORD =-1
      ISECSB=3
      JFBLKB(ISECSB)=50          !RESULTS IN OUTPUT START BLOCK =51
      GO TO 30
C***READ INDEX OF PREVIOUS STORED RECORD
10      ISCAN=1
20      READ(11'ISCAN) IRB,ISECSB,MCHANB,TSAMPB,ISUBNB,IHOSNB,ITSTNB,
1          IPOLB,SCALFB,OFSETB,JSBLKB,JFBLKB,JFWRDR,NSAMPB
      IF(IRB.LT.0) GO TO 30
      ISCAN=ISCAN+1
      GO TO 20
C***SET OUTPUT RECORD NUMBER AND STARTING OUTPUT BLOCK NUMBER
30      IRO=IRB-1          !OUTPUT REC NUM::STORED AS NEGATIVE
      LBLK=JFBLKB(ISECSB)  !OUTPUT STARTING BLOCK LESS ONE
C***OPEN INPUT FILE
      CALL ASSIGN(40,'DK3:ADC.DAT',11,'OLD')
      DEFINE FILE 40(820,256,U,IF40)
C***INITIALIZE INDEX VARIABLES
      IBLK=INBLK          !INPUT BLOCK INDEX
      JBLK=LBLK          !OUTPUT BLOCK INDEX
      NS=NNT              !SAMPLE COUNTER

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50      READ(40'IBLK) IDATA
        IPLK=IBLK+1
C***WRITE A BLOCK OF OUTPUT DATA
        JBLK=JBLK+1
        WRITE(11'JBLK) IDATA
        NS=NS-16
        IF(NS.GT.16) GO TO 50
C***READ LAST INPUT BLOCK
        READ(40'IBLK) IDATA
C***COMPUTE NUMBER OF SAMPLES IN LAST BLOCK TO BE ZERDED
        J=NS*16+1
C***FILL REMAINDER OF LAST OUTPUT BLOCK WITH ZERO
        IF(J.GT.256) GO TO 90
        DO 80 JI=J,256
80      IDATA(JI)=0
C***WRITE LAST OUTPUT BLOCK
90      JBLK=JBLK+1
        WRITE(11'JBLK) IDATA
C***STORE INDEXING PARAMETERS FOR THIS SECTION
        JSBLK(1)=LBLK+1
        JFBLK(1)=JBLK
        JFWRD(1)=NS*16
        NSAMP(1)=NNT
        CALL CLOSE(40)
C***DISPLAY PREVIOUS AND CURRENT RECORD INFO ON TX SCREEN
130     IF(IRT.NE.1) GO TO 140
        WRITE(100,2000) -IRB,ISUBNB,IHOSNB,ITSTNB
        WRITE(100,2010) ISECSB,JSBLKB(1),JFBLKB(1),JFWRDB(1)
140     WRITE(100,2000) -IRO,ISUBN,IHOSN,ITSTN
        WRITE(100,2010) ISECS,JSBLK(1),JFBLK(1),JFWRD(1)
C***COMPUTE AND COMPARE TOTAL DATA SAMPLES TO TOTAL STORED SAMPLES
        LOT=(JFBLK(1)-JSBLK(1))*16+JFWRD(1)/16
        WRITE(100,2090) LOT,NSAMP(1)
C***IF DATA LOOKS GOOD-RESTORE PREVIOUS RECORD INDEX WITH POSITIVE
C***RECORD NUMBER AND STORE CURRENT RECORD INDEX WITH NEGATIVE
C***RECORD NUMBER
        WRITE(100,2070)
        READ(1KB,1020) IY
        IF(IY.NE.IYES) CALL CLOSE(11)
        IF(IY.NE.IYES) STOP 'DATA TRANSFER NOT COMPLETED'
        IF(IRT.NE.1) GO TO 170
        IRB=-IRB
        WRITE(11'IRB) IRB,ISECSB,MCHANB,TSAMPB,ISUBNB,IHOSNB,ITSTNB,
1         IPOLB,SCALFB,OFFSETB,JSBLKB,JFBLKB,JFWRDB,NSAMPB
C***LOAD UNUSED SECTION INDEX ARRAY POSITIONS WITH ZERO
170     DO 180 I=2,42
        JSBLK(I)=0
        JFBLK(I)=0
        JFWRD(I)=0
180     NSAMP(I)=0
C***COMPUTE SAMPLE TIME IN MILLISECS
        TSAMP=FLOAT(NCOUNT)
        TSAMP=TSAMP*10.0**((ITEN-3)
        WRITE(11'-IRO) IRO,ISECS,MCHAN,TSAMP,ISUBN,IHOSN,ITSTN,IPOL,
1         SCALF,OFFSET,JSBLK,JFBLK,JFWRD,NSAMP
        CALL CLOSE(11)
C***SET PRINTED OUTPUT FLAG
        WRITE(100,2080)
        READ(1KB,1020) IY1
        IF(IY1.NE.IYES) GO TO 200
        WRITE(8,2020)
        WRITE(8,2000) -IRO,ISUBN,IHOSN,ITSTN
        WRITE(8,2010) ISECS,JSBLK(1),JFBLK(1),JFWRD(1)
200     CALL EXIT
1000    FORMAT(2I7)
1010    FORMAT(14)

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1020  FORMAT(A2)
2000  FORMAT(1H , 'RECORD NUM:', I4, 5X, 'SUBJECT NUM:', I4, 5X,
1    'HOSP NUM:', I6, 5X, 'TEST NUM:', I4)
2010  FORMAT(1H , 10X, I3, ' SECTIONS OF DATA', 5X, 'INITIAL BLOCK:',
1    I4, 5X, 'FINAL BLOCK:', I4/)
2020  FORMAT(1H , 19X, 'STORED ON S.A.D.')
2030  FORMAT(20X, 'DATA STORAGE ON S.A.D.'/10X,
1    'ENTER INPUT RECORD NUM AND NUM OF CHANNELS')
2040  FORMAT(10X, 'ENTER SUBJECT NUM AND HOSPITAL NUM')
2050  FORMAT(10X, 'ENTER TEST NUMBER')
2060  FORMAT(10X, 'ENTER SECTION NUMBER(NEGATIVE TO STOP)')
2070  FORMAT(10X, 'DOES IT LOOK OK? (YES/NO)')
2080  FORMAT(10X, 'DO YOU WANT PRINTED OUTPUT? (YES/NO)')
2090  FORMAT(5X, I6, ' STOKED SAMPLES', 5X, I6, ' DATA SAMPLES')
      END

```

```

C***          PROGRAM DATCON
C***  THIS PROGRAM RECOVERS INTEGER DATA STORED IN DP1:RAWACC.DAT
C***ON DISC S.A.D., CONVERTS IT TO REAL NUMPEPS, AND STORES IT ON
C***SY:CODATA.DAT; INDEX INFORMATION IS STORED ON SY:INDACC.DAT.
C***
C***          TASK BUILD AS: DATCON=DATCON,[1,1]F4POTS/LB
C***          UNITS=14          MAXBUF=512
      DIMENSION IDATA(256),IPOL(16),SCALF(16),OFSET(16),JSBLK(42)
      DIMENSION JFBLK(42),JFWRD(42),NSAMP(42),CODATA(16,6)
      DIMENSION IPOS(3),IR(3),ISUB(3),IHOS(3),ITST(3),ISBL(3)
      DIMENSION IFBL(3),KEND(3),TSAMPL(3),DATA(16)
      LOGICAL*1 IDATE(9),ITIME(8)
      COMMON /ASV/IF11,IF12,IF14
      DATA IYES/'YE'/
      IKB=5
      IOD=5
      CALL ASSIGN(8,'SY:PRNTIT,LST;1')
      CALL FDBSET(8,'NEW')
      C2123=272.5528
      C13=38.93611
C***ENTER INPUT RECORD NUMBER
10      WRITE(IOD,2000)
      READ(IKB,1000) IRA
C***READ INPUT INDEXES
      CALL ASSIGN(11,'DP1:[167,15]RAWACC.DAT;1')
      DEFINE FILE 11(4250,256,U,IF11)
      CALL FDBSET(11,'READONLY')
      READ(11'IRA) IRB,ISECS,MCHAN,TSAMP,ISUBN,IHOSN,ITSTN,IPOL,
1          SCALF,OFSET,JSBLK,JFBLK,JFWRD,NSAMP
C***DISPLAY ON TX SCREEN RECORD NUM,SUBJECT NUM,HOSP NUM,TEST NUM
      IF(IRB.LT.0) IRB=-IRB
      WRITE(IOD,2010) IRB,ISUBN,IHOSN,ITSTN
C***IF NOT CORRECT RECORD, THEN RESTART
      WRITE(IOD,2020)
      READ(IKB,1010) IY
      IF(IY.NE.IYES) CALL CLOSE(11)
      IF(IY.NE.IYES) GO TO 10
C***OPEN OUTPUT FILES
      CALL ASSIGN(12,'SY:CODATA.DAT;1')
      CALL FDBSET(12,'NEW')
      DEFINE FILE 12(200,256,U,IF12)
C***INITIALIZE INDEXING VARIABLES
      J=0          !CHANNEL NUMBER
      K=1          !INPUT DATA SAMPLE INDEX
      L=0          !INPUT DATA WORD INDEX
      INBLK=JSBLK(1) !INPUT DATA STARTING BLOCK
      KI=1         !OUTPUT DATA SAMPLE INDEX
      ISBLK=1       !OUTPUT DATA STARTING BLOCK
      IFBLK=ISBLK   !OUTPUT BLOCK INDEX
      LOT=0
      DO 20 IS=1,ISECS
20      LOT=LOT+NSAMP(IS)          !NUM OF SAMPLES
C***READ INITIAL BLOCK OF INPUT DATA
      READ(11'INBLK) IDATA
50      J=J+1
      IF(J.LE.MCHAN) GO TO 120
C***WHEN ALL CHANNELS OF ONE SAMPLE CONVERTED ,COMPUTE CODATA
      CODATA(KI,1)=-DATA(11)*C2123
      CODATA(KI,2)=-((DATA(9)-DATA(12))*C13
      CODATA(KI,3)=-DATA(10)*C2123
      CODATA(KI,4)=-((DATA(9)+DATA(12))*C13
      CODATA(KI,5)=(DATA(1)+DATA(2))*0.5
      CODATA(KI,6)=(DATA(3)+DATA(4))*0.5

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      CODATA(KI,7)=(DATA(5)+DATA(6))*0.5
      CODATA(KI,8)=(DATA(7)+DATA(8))*0.5
C***RESET CHANNEL INDEX; INCREMENT SAMPLE AND OUTPUT ARRAY INDEXES
110      J=1
          K=K+1
          KI=KI+1
C***TEST FOR END OF THIS SECTION OF INPUT DATA
      IF(K.GT.LOT) GO TO 150
C***INCREMENT INPUT DATA WORD INDEX AND TEST FOR END OF BLOCK
120      L=L+1
          IF(L.LE.256) GO TO 130
C***RESET WORD INDEX AND INCREMENT BLOCK NUMBER
          L=1
          INBLK=INBLK+1
C***READ ANOTHER BLOCK OF INPUT DATA
      READ(11*INBLK) IDATA
C***IF PEAL DATA ARRAY FULL,WRITE TO DISC
130      IF(KI.LE.16) GO TO 140
          WRITE(12*IFBLK) ((CODATA(KIL,IL),IL=1,8),KIL=1,16)
C***RESET ARRAY INDEX AND INCREMENT OUTPUT BLOCK INDEX
          KI=1
          IFBLK=IFBLK+1
C***CONVERT SINGLE INTEGER SAMPLE TO SCALED,OFFSET REAL DATA(G-S)
140      DATA(J)=FLOAT(IDATA(L)-512*(IPOL(J)-1))*SCALEF(J)/204.8048
          1      -OFFSET(J)
          GO TO 50
C***STORE ZERO IN REMAINDER OF LAST CODATA BLOCK
C***AND WRITE LAST BLOCK TO DISC FILE
150      IF(KI.GT.16) GO TO 170
          DO 160 KA=KI,16
          DO 160 IL=1,8
160      CODATA(KA,IL)=0.0
170      WRITE(12*IFBLK) ((CODATA(KIL,IL),IL=1,8),KIL=1,16)
C***CLOSE OPEN FILES
      CALL CLOSE(12)
      CALL CLOSE(11)
C***COMPUTE INDEXING INFORMATION
      DO 180 I=1,3
          IPOS(I)=0
          IR(I)=IRB
          ISUB(I)=ISUBN
          IHOS(I)=IHOSN
          ITST(I)=ITSTN
180      TSAMPL(I)=TSAMP
          IF(ISECS.NE.3) GO TO 200
          DO 190 I=1,3
          ISBL(I)=JSBLK(I)-JSBLK(1)+1
          IFBL(I)=JFBLK(I)-JSBLK(1)+1
190      KEND(I)=JFWRD(I)/2
          GO TO 220
200      IF(ISECS.NE.1) STOP 'NOT 1 OR 3 DATA SECTIONS'
          ISBL(1)=ISBLK
          IFBL(1)=IFBLK
          KEND(1)=(KI-1)*8
          DO 210 I=2,3
          ISBL(I)=0
          IFBL(I)=0
210      KEND(I)=0
C***INSURE CORRECT NUMBER OF SAMPLES STORED IN CODATA
220      KENDK=(KI-1)*8
          NSAMP2=(IFBLK-ISBLK)*16+KENDK/8
          WRITE(10D,2030) NSAMP2,LOT
          WRITE(10D,2010) IP(1),ISUB(1),IHOS(1),ITST(1)
          DO 230 I=1,ISECS
230      WRITE(10D,2070) I,ISBL(I),IFBL(I),KEND(I)
D      WRITE(10D,2140)

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D      READ(IKB,1010) IY1
D      IF(IY1.NE.IYES) GO TO 250
C***STORE INDEXING INFORMATION
      CALL ASSIGN(14,'SY:INDACC.DAT;1')
      CALL FDBSET(14,'NEW')
      DEFINE FILE 14(1,30,U,IF14)
      WRITE(14'1) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMPL
      CALL CLOSE(14)
C***SET PRINTED OUTPUT FLAG
      IY2=IYES                      !SET TO ALWAYS PRINT
      IF(IY2.NE.IYES) GO TO 250
      CALL DATE(IDATE)
      CALL TIME(ETIME)
      WRITE(8,2080) IDATE,ETIME
      WRITE(8,2060)
      WRITE(8,2010) IR(1),ISUB(1),IHOS(1),ITST(1)
      DO 240 I=1,ISECS
240    WRITE(8,2070) I,ISBL(I),IFBL(I),KEND(I)
      CALL CLOSE(8)
250    CALL EXIT
1000    FORMAT(I4)
1010    FORMAT(A2)
2000    FORMAT(20X,'STORE DATA IN CODATA'/10X,
1      'ENTER INPUT RECORD NUMBER')
2010    FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1      'HOSP NUM:',I6,5X,'TEST NUM:',I6)
2020    FORMAT(10X,'IS THIS CORRECT RECORD? (YES/NO)')
2030    FORMAT(10X,'CONVERTED',I6,X,'SAMPLES STORED',I6,X,
1      'SAMPLES')
2040    FORMAT(10X,'DOES IT LOOK OK? (YES/NO)')
2050    FORMAT(10X,'DO YOU WANT PRINTED OUTPUT? (YES/NO)')
2060    FORMAT(1H,'19X','DATA CONVERTED AND STORED IN SY:CODATA FOR')
2070    FORMAT(1H,'SECTION:',I2,2X,'FIRST BLOCK:',I4,2X,
1      'LAST BLOCK:',I4,2X,'LAST WORD:',I4)
2080    FORMAT(1H,'10X','PROCESSED ON ',9A1,2X,'AT ',8A1)
      END

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```

C***          PROGRAM STADAT
C***  THIS PROGRAM RECOVERS INTEGER DATA STORED IN DP1:RAWACC.DAT
C***ON DISC S.A.D. AND CONVERTS IT TO REAL NUMBERS(IN G-S).
C***STATISTICS FOR EACH SECTION OF DATA ARE COMPUTED AND STORED
C***ON SY:COSTAT.DAT.
C***
C***          TASK BUILD AS: STADAT=STADAT,[1,1]F4POTS/LB
C***                      UNITS=13          MAXBUF=512
C***
C***          DIMENSION IDATA(256),IPOL(16),SCALF(16),OFFSET(16),JSBLK(42)
C***          DIMENSION JFBLK(42),JFWRD(42),NSAMP(42),CODATA(16,6)
C***          DIMENSION DATA(16),STATS(6,16)
C***          COMMON /ASV/IF11,IF13
C***          DATA IYES/'YE'/
C***          IKR=5
C***          IOD=5
C***          CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
C***          CALL FDBSET(8,'APPEND')
C***          C2123=272.5528
C***          C13=38.93611
C***ENTER INPUT RECORD NUMBER
10      WRITE(10,2000)
        READ(IKR,1000) IR
C***READ INPUT INDEXES
        CALL ASSIGN(11,'DP1:[167,15]RAWACC.DAT;1',22)
        DEFINE FILE 11(4250,256,U,IF11)
        READ(11'IR) IRB,ISECS,MCHAN,TSAMP,ISUBN,IHOSN,ITSTN,IPOL,
1          SCALF,OFFSET,JSBLK,JFBLK,JFWRD,NSAMP
C***DISPLAY ON TX SCREEN RECORD NUM,SUBJECT NUM,HOSP NUM,TEST NUM
        IF(IRB.LT.0) IRB=-IRB
        WRITE(10,2010) IRB,ISUBN,IHOSN,ITSTN
C***IF NOT CORRECT RECORD, THEN RESTART
        WRITE(10,2020)
        READ(IKR,1010) IY
        IF(IY.NE.IYES) CALL CLOSE(11)
        IF(IY.NE.IYES) GO TO 10
C***OPEN OUTPUT FILE
        CALL ASSIGN(13,'SY:COSTAT.DAT;1',16)
        CALL FDBSET(13,'NEW')
        DEFINE FILE 13(3,192,U,IF13)
C***SET INDEXES FOR CONVERSION AND STATISTICS COMPUTATION LOOP
        IS=1                      !SECTION NUMBER
        J=0                      !CHANNEL NUMBER
        L=0                      !INPUT DATA WORD INDEX
        INBLK=JSBLK(IS)          !INPUT DATA STARTING BLOCK
        NSAMP2=0
C***READ INITIAL BLOCK OF INPUT DATA
        READ(11'INBLK) IDATA
30      K=1                      !SECTION SAMPLE INDEX
        LOT=NSAMP(IS)            !NUM SAMPLES IN THIS SECTION
        RLOT=FLOAT(LOT)
50      J=J+1
        IF(J.LE.MCHAN) GO TO 120
C***WHEN ALL CHANNELS OF ONE SAMPLE CONVERTED TO G-S, COMPUTE
C*** AND STORE STATISTICS SUMMATIONS
C***ON FIRST SAMPLE OF EACH SECTION, STORE INITIAL VALUES
60      IF(K.NE.1) GO TO 90
        DO 80 JS=1,16
        DO 70 IK=1,5
70      STATS(IK,JS)=DATA(JS)
80      STATS(6,JS)=DATA(JS)*DATA(JS) !TEMP STORE SUMMATION X**2
        GO TO 110
C***STORE SUMMATION AND MAX,MIN FOR COMPUTING STATISTICS
        DO 100 JS=1,16

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        STATS(1,JS)=STATS(1,JS)+DATA(JS)
        STATS(6,JS)=STATS(6,JS)+DATA(JS)*DATA(JS)
        IF(DATA(JS).GT.STATS(2,JS)) STATS(2,JS)=DATA(JS)
100      IF(DATA(JS).LT.STATS(3,JS)) STATS(3,JS)=DATA(JS)
C***RESET CHANNFL INDEX AND INCREMENT SAMPLE INDEX
110      J=1
        K=K+1
C***TEST FOR END OF THIS SECTION OF INPUT DATA
        IF(K.GT.LOT) GO TO 190
C***INCREMENT INPUT DATA WORD INDEX AND TEST FOR END OF BLOCK
120      L=L+1
        IF(L.LE.256) GO TO 140
C***RESET WORD INDEX AND INCREMENT BLOCK NUMBER
        L=1
        INBLK=INBLK+1
C***READ ANOTHER BLOCK OF INPUT DATA
        READ(11,INBLK) IDATA
C***CONVERT SINGLE INTEGER SAMPLE TO SCALED, OFFSET REAL DATA(G-S)
140      DATA(J)=FLOAT(IDATA(L)-512*(IPOL(J)-1))*SCALF(J)/204.8048
        1      -OFSEI(J)
        GO TO 50
C***COMPUTE STATISTICS AND STORE ON FILE COSTAT.DAT
190      DO 200 JS=1,16
        STATS(1,JS)=STATS(1,JS)/RLOT
        STATS(4,JS)=(STATS(6,JS)-STATS(1,JS)*STATS(1,JS)
        1      *RLOT)/RLOT
200      STATS(5,JS)=SQRT(STATS(4,JS))
        DO 210 JS=1,7,2
        STATS(6,JS)=(STATS(1,JS)+STATS(1,JS+1))*0.5
210      STATS(6,JS+1)=STATS(6,JS)
        WRITE(13,IS) ((STATS(IK,JS),IK=1,6),JS=1,16)
C***INCREMENT SECTION NUMBER AND IF ALL SECTIONS NOT COMPLETED LOOP
        IS=IS+1
        J=0
        NSAMP2=NSAMP2+K-1
        IF(IS.LE.ISECS) GO TO 30
C***CLOSE INPUT FILE
        CALL CLOSE(11)
C***INSURE CORRECT NUMBER OF SAMPLES USED
        NSAMPR=0
        DO 220 I=1,ISECS
220      NSAMPR=NSAMPR+NSAMP(I)
        WRITE(10D,2030) NSAMP2,NSAMPR
D        WRITE(10D,2040)
D        READ(IK8,1010) IY1
D        IF(IY1.NE.IYES) GO TO 300
C***SET PRINTED OUTPUT FLAG
        IY2=IYES
        IF(IY2.NE.IYES) GO TO 250
        WRITE(8,2060)
        WRITE(8,2010) IRB,ISURN,IHOSN,ITSTN
C***PRINT STATISTICS IF FLAG SET
        IY3=IYES
        IF(IY3.NE.IYES) GO TO 300
        DO 260 ISEC=1,ISECS
        READ(13,ISEC) ((STATS(ISA,JS),ISA=1,6),JS=1,16)
        WRITE(8,2080) ISEC
        WRITE(8,2200) JSBLK(ISEC),JFBLK(ISEC),JFWRD(ISEC)
        WRITE(8,2090)
        WRITE(8,2110) (STATS(1,I),I=1,8)
        WRITE(8,2120) (STATS(2,I),I=1,8)
        WRITE(8,2130) (STATS(3,I),I=1,8)
        WRITE(8,2140) (STATS(4,I),I=1,8)
        WRITE(8,2150) (STATS(5,I),I=1,8)
        WRITE(8,2160) (STATS(6,I),I=1,8)

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WRITE(8,2110) (STATS(1,I),I=9,16)
WRITE(8,2120) (STATS(2,I),I=9,16)
WRITE(8,2130) (STATS(3,I),I=9,16)
WRITE(8,2140) (STATS(4,I),I=9,16)
WRITE(8,2150) (STATS(5,I),I=9,16)
260  WRITE(8,2160) (STATS(6,I),I=9,16)
      CALL CLOSE(8)
300  CALL CLOSE(13)
250  CALL EXIT
1000 FORMAT(I4)
1010 FORMAT(A2)
2000 FORMAT(20X,"DATA STATISTICS COMPUTING"/10X,
1      "ENTER INPUT RECORD NUMBER")
2010 FORMAT(1H,"RECORD NUM:",I3,5X,"SUBJECT NUM:",I3,5X,
1      "HOSP NUM:",I6,5X,"TEST NUM:",I6/)
2020 FORMAT(10X,"IS THIS CORRECT RECORD? (YES/NO)")
2030 FORMAT(10X,"CONVERTED",I6,X,"SAMPLES STORED",I6,X,
1      "SAMPLES")
2040 FORMAT(10X,"DOES IT LOOK OK? (YES/NO)")
2050 FORMAT(10X,"DO YOU WANT PRINTED OUTPUT? (YES/NO)")
2060 FORMAT(1H,"19X,
1      "STATISTICS COMPUTED AND STORE IN SY:COSTAT FOR")
2080 FORMAT(1H,"15X,"STATISTICS FOR SECTION",I3)
2090 FORMAT(11X,"CH(1)",9X,"CH(2)",9X,"CH(3)",9X,"CH(4)",9X,
1      "CH(5)",9X,"CH(6)",9X,"CH(7)",9X,"CH(8)")
2100 FORMAT(11X,"CH(9)",8X,"CH(10)",8X,"CH(11)",8X,"CH(12)",8X,
1      "CH(13)",8X,"CH(14)",8X,"CH(15)",8X,"CH(16)")
2110 FORMAT(2X,"MEAN",2X,8G14.7)
2120 FORMAT(2X,"MAX",3X,8G14.7)
2130 FORMAT(2X,"MIN",3X,8G14.7)
2140 FORMAT(2X,"VAR",3X,8G14.7)
2150 FORMAT(2X,"STD DV",8G14.7)
2160 FORMAT(2X,"PMV",3X,8G14.7)
2200 FORMAT(1H,"FIRST BLOCK:",I4,2X,"LAST BLOCK:",I4,2X,
1      "LAST WORD:",I4)
2220 FORMAT(10X,"DO YOU WANT STATISTICS PRINTED? (YES/NO)")
      END

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C***      PROGRAM FILDAT
C***      THIS PROGRAM FILTERS DATA IN SY:CODATA.DAT USING AN 8TH
C***ORDER RECURSIVE BUTTERWORTH FILTER. THE DATA IN SY:CODATA.DAT
C***IS REPLACED BY THE FILTERED DATA.
C***      NOTE: ONLY DATA IN CODATA(KI,1 TO 3) ARRAY POSITIONS ARE FILTERED
C***
C***      TASK BUILD AS FILDAT=FILDAT,BNDPAS,[1,1]F4POTS/LB
C***      UNITS=14      MAXBUF=512
      DIMENSION CODATA(16,8),SIDATA(3200),IPOS(3),IR(3),ISUB(3)
      DIMENSION IHOS(3),ITST(3),JSBL(3),IFBL(3),KEND(3),TSAMP(3)
      COMMON /ASV/IF12,IF14
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1')
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(IOD,2000)
2000      FORMAT(20X,'CODATA FILTERING')
1000      FORMAT(14)
C***ASSIGN AND DEFINE INPUT/OUTPUT FILE
      CALL ASSIGN(12,'SY:CODATA.DAT;1')
      CALL FDBSET(12,'OLD')
      DEFINE FILE 12(200,256,U,IF12)
C***READ POINTER INDEX FILE
      CALL ASSIGN(14,'SY:INDACC.DAT;1')
      CALL FDBSET(14,'OLD')
      DEFINE FILE 14(1,30,U,IF14)
      READ(14'1) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(14)
C***ENTER LOWER AND UPPER BANDPASS FREQUENCIES
      FC1=0.50      !LOWER SET TO 0.50 HZ
      FC2=10.0      !UPPER SET TO 10.0 HZ
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(1)
      ILSBLK=IFBL(1)
      KENDIT=KEND(1)
      IF(IFBL(3).NE.0) ILSBLK=IFBL(3)
      IF(KEND(3).NE.0) KENDIT=KEND(3)
      LS=16
      LOT=LS*(ILSBLK-ISBL(1))+KENDIT/8
      FS=1000.0/TSAMP(1)
      II=1
C***LOAD ALL SAMPLES OF CODATA(=,1) INTO SIDATA
10      READ(12'IBLK) ((CODATA(KI,I),I=1,8),KI=1,LS)
      IBLK=IBLK+1
      DO 20 KB=1,LS
      IND=(IBLK-ISBL(1)-1)*16+KB
20      SIDATA(IND)=CODATA(KB,II)
      IF(IBLK.EQ.ILSBLK) LS=KENDIT/8
      IF(IBLK.GT.ILSBLK) GO TO 40
      GO TO 10
C***INCREMENT ARRAY POSITION AND IF LAST POSITION FILTERED EXIT LOOP
30      II=II+1
      IF(II.GT.3) GO TO 90
C***FILTER ONE ARRAY POSITION OF DATA(STORED IN SIDATA)
40      CALL BNDPAS(SIDATA,LOT,FC1,FC2,FS)
C***RESET BLOCK AND WORD INDEXES
      IBLK=ISBL(1)
      LS=16
C***RELOAD CODATA TO REPLACE FILTERED ARRAY POSITION AND TO
C***LOAD SIDATA WITH NEXT ARRAY POSITION TO BE FILTERED
50      READ(12'IBLK) ((CODATA(KI,I),I=1,8),KI=1,LS)

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      IOBLK=IBLK
      IBLK=IBLK+1
      DO 60 KB=1,LS
      IND=(IOBLK-ISBL(1))*16+KB
C***LOAD FILTERED DATA INTO CODATA
      CODATA(KB,II)=SIDATA(IND)
      IF(II.GE.3) GO TO 60
C***LOAD NEXT ARRAY POSITION TO BE FILTERED INTO SIDATA
      SIDATA(IND)=CODATA(KB,II+1)
60    CONTINUE
C***WRITE FILTERED DATA TO DISC FILE
      WRITE(12'IOBLK) ((CODATA(KI,I),I=1,8),KI=1,LS)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
      IF(IBLK.EQ.ILSBLK) LS=KENDIT/8
C***TEST FOR END OF INPUT DATA
      IF(IBLK.GT.ILSBLK) GO TO 30
      GO TO 50
C***CLOSE OPEN FILE
90    CALL CLOSE(12)
C***WRITE ADJUSTMENT INFO ON TERMINAL SCREEN
      WRITE(100,2030)
2030  FORMAT(10X,'CODATA FILTERING COMPLETED ON:')
      WRITE(100,2060) IP(1),ISUB(1),IHOS(1),ITST(1),IPOS(1)
2060  FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1     'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I4)
      WRITE(100,2070) FC1,FC2
2070  FORMAT(10X,'BANDPASS FREQUENCIES =',F9.2,' TO',F9.2,' HZ')
      KENDR=(KI-1)*8
      WRITE(100,2110) ISBL(1),IOBLK,KENDR,LOT
C***SET PRINTED OUTPUT FLAG
      IY1=IYES                                !SET TO ALWAYS PRINT
      IF(IY1.NE.IYES) GO TO 100
      WRITE(8,2030)
      WRITE(8,2060) IP(1),ISUB(1),IHOS(1),ITST(1),IPOS(1)
      WRITE(8,2070) FC1,FC2
      WRITE(8,2110) ISBL(1),IOBLK,KENDR,LOT
2110  FORMAT(1H,'FIRST BLOCK:',I4,2X,'LAST BLOCK:',I4,2X,
1     'LAST WORD:',I4,2X,'NUM. OF SAMPLES:',I4)
      CALL CLOSE(8)
100   CALL EXIT
      END

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      SUBROUTINE BNDPAS(ARRAY,N,F1,F2,FS)
C***AN 8TH ORDER BUTTERWORTH FILTER WHICH PASSES FREQUENCIES BETWEEN
C***F1 AND F2 HZ IS APPLIED IN BOTH DIRECTIONS TO REMOVE PHASE
C***SHIFTS. THE DATA SAMPLING FREQUENCY IS "FS" HZ, AND THE NUMBER
C***OF DATA POINTS IS N. THIS VERSION DOES NOT EXTEND ARRAY SIZE
C***OR REMOVE TRENDS.
C***IF FREQUENCY F2 IS GREATER THAN OR EQUAL TO HALF THE
C***SAMPLING FREQUENCY, THE DATA IS NOT FILTERED.
      DIMENSION ARRAY(1)
      DOUBLE PRECISION TEMP(10),AFILT(9),XPI,XL1,XL2,CT,WA1,WA2,W,
1      A,B,A0,A1,A2,A3,S0,S1,S2,S3,S4,S5,S6,S7,S8,DS
      IF(F2.GE.FS/2.0) GO TO 120
      XPI=3.1415926535897
      XL1=XPI*F1/FS
      XL2=XPI*F2/FS
      CT=DCOS(XL1+XL2)/DCOS(XL1-XL2)
      DS=DSIN(2.0*XL1)
      IF(DS.LT.1.0E-10) DS=1.0E+10
      WA1=(CT-DCOS(2.0*XL1))/DS
      WA2=(CT-DCOS(2.0*XL2))/DSIN(2.0*XL2)
      W=ABS(WA1)
      IF(W.LT.ABS(WA2)) W=ABS(WA2)
      A=DSIN(XPI/8.0)
      B=DCOS(XPI/8.0)
C***CALCULATION OF COEFFICIENTS
      A0=W**W**W**W
      A1=(A+B)*W
      A2=(A+B)*(A+B)*W**W
      A3=(A+B)*W**W**W
      S8=1.0+2.0*(A1+A2+A3)+A0
      S7=-4.0*CT*(2.0+2.0*A2+3.0*A1+A3)
      S6=4.0*(1.0+A1-A3-A0+2.0*CT*CT*(3.0+A2+3.0*A1))
      S5=-4.0*CT*(6.0-2.0*A2+3.0*A1-3.0*A3+4.0*CT*CT*(2.0+A1))
      S4=2.0*(3.0-2.0*A2+3.0*A0+8.0*CT*CT*(3.0-A2+CT*CT))
      S3=-4.0*CT*(6.0-2.0*A2-3.0*A1+3.0*A3+4.0*CT*CT*(2.0-A1))
      S2=4.0*(1.0-A1+A3-A0+2.0*CT*CT*(3.0+A2-3.0*A1))
      S1=-4.0*CT*(2.0+2.0*A2-3.0*A1-A3)
      S0=1.0+2.0*A2-2.0*A1-2.0*A3+A0
C***STORE INITIAL VALUE
      TEMP(10)=ARRAY(1)
C***ZERO ALL OTHER ELEMENTS.
      DO 30 K=1,9
          TEMP(K)=0.0
30      AFILT(K)=0.0
C***SUBTRACT THE INITIAL VALUE FROM ALL VALUES.
      DO 40 K=1,N
          40 ARRAY(K)=ARRAY(K)-TEMP(10)
C***APPLY FILTER TO ELEMENTS 1 TO N.
      DO 50 K=1,N
          TEMP(9)=ARRAY(K)
          AFILT(9)=(A0*(TEMP(9)-4.0*TEMP(7)+6.0*TEMP(5)-4.0*TEMP(3)
1          +TEMP(1))-(S7*AFILT(8)+S6*AFILT(7)+S5*AFILT(6)+S4*AFILT(5)
2          +S3*AFILT(4)+S2*AFILT(3)+S1*AFILT(2)+S0*AFILT(1)))/S8
          ARRAY(K)=AFILT(9)
          DO 50 KK=1,8
              TEMP(KK)=TEMP(KK+1)
50      AFILT(KK)=AFILT(KK+1)
C***REZERO DOUBLE PRECISION ARRAYS
      DO 70 KK=1,9
          TEMP(KK)=0.0
70      AFILT(KK)=0.0
C***APPLY FILTER IN REVERSE DIRECTION.
      DO 80 KK=N,N-1,N-2,N-3,N-4,N-5,N-6,N-7,N-8,N-9

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      K=N-KN+1
      TEMP(9)=ARRAY(K)
      AFILT(9)=(A0*(TEMP(9)-4.0*TEMP(7)+6.0*TEMP(5)-4.0*TEMP(3)
1 +TEMP(1))-(S7*AFILT(8)+S6*AFILT(7)+S5*AFILT(6)+S4*AFILT(5)
2 +S3*AFILT(4)+S2*AFILT(3)+S1*AFILT(2)+S0*AFILT(1)))/S8
      ARRAY(K)=AFILT(9)
      DO 80 KK=1,8
        TEMP(KK)=TEMP(KK+1)
80      AFILT(KK)=AFILT(KK+1)
C***READD INITIAL VALUE TO FILTERED VALUES TO CORRECT TO ORIGINAL IC'S.
      TEMPAR=ARRAY(1)
      DO 90 K=1,N
        90 ARRAY(K)=ARRAY(K)+TEMP(10)-TEMPAR
100 RETURN
120      WRITE(100,4000)
        WRITE(8,4000)
4000      FORMAT(10X,'*****F2 GREATER THAN FS/2,*****')
        RETURN
      END

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C***          PROGRAM SWPDAT
C***  THIS PROGRAM MOVES WALKING DATA (SECTION 2) FROM
C***  SY:CODATA.DAT TO POSITION 1 IN SY:CODATB.DAT
C***
C***          TASK BUILD AS: SWPDAT=SWPDAT,[1,1]F4POTS/LB
C***          UNITS=14          MAXBUF=512
C***          DIMENSION CODATA(16,8),STATS(6,16),IPOS(3),IR(3),ISUB(3),
1          ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3),TRDATA(32,8),
2          IHOS(3)
COMMON /ASV/IF12,IF13,IF14,IF17,IF19,IF20
DATA IYES/'YE'/,IND/'NO'/
IKB=5
IOD=5
CALL ASSIGN(8,'SY:PRNTIT.LST;1')
CALL FDBSET(8,'APPEND')
C***READ INPUT INDEX FILE
CALL ASSIGN(9,'SY:INDACC.DAT;1')
DEFINE FILE 9(1,30,U,IF14)
READ(9'1) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
CALL CLOSE(9)
IPOST=1          !SET UP SO ALWAYS LOADED INTO POSITION 1
DO 10 I=1,3
10  IPOS(I)=IPOST
C***OPEN CODATA INPUT/OUTPUT FILES
CALL ASSIGN(10,'SY:CODATB.DAT;1')
DEFINE FILE 10(130,256,U,IF12)
CALL FDBSET(10,'NEW')
CALL ASSIGN(11,'SY:CODATA.DAT;1')
DEFINE FILE 11(200,256,U,IF17)
CALL FDBSET(11,'READONLY')
C***SET INDEXES
INBLK=ISBL(2)          !SECTION 2 STARTING BLOCK
ISBLK=1                !STARTING OUTPUT BLOCK
IF(IPOST.EQ.2) ISBLK=ISBLK+130
IF(IPOST.EQ.3) ISBLK=ISBLK+260
IFBLK=ISBLK            !OUTPUT BLOCK INDEX
LSS=16                !FINAL DATA SAMPLE INDEX
KFIRST=1              !INITIAL SAMPLE FLAG
KS=KEND(1)/8
IF(KS.FO.16) KS=0
KSB=16-KS
LOT=((IFBL(2)-ISBL(2))*16+(KEND(2)/8)-KS)
ILOT=LOT
LS=16                !SECTION LAST SAMPLE INDEX
C***BEGINNING OF LOOP
C***READ BLOCK OF INPUT AND INDEX BLOCK
60  READ(11'INBLK) ((CODATA(KIL,IL)),IL=1,8),KIL=1,LSS)
    INBLK=INBLK+1
    LOT=LOT-LSS
    IF(KFIRST.NE.1) GO TO 70
    LOT=LOT+LSS-KSB
    GO TO 150
70  IF(LOT.LE.0) LS=LSS+LOT
C***FILL REMAINDER OF OUTPUT ARRAY
DO 80 IL=1,8
DO 80 KIB=KSB+1,KSB+LS
80  TRDATA(KIB,IL)=CODATA(KIB-KSB,IL)
    IF(KFIRST.EQ.1) KFIRST=0
    IF(KIB.LE.17) GO TO 100
C***WRITE ONE COMPLETE ARRAY BLOCK TO DISC
    WRITE(10'IFBLK) ((TRDATA(KIL,IL)),IL=1,8),KIL=1,16)
    IFBLK=IFBLK+1
C***SNAP REMAINDER OF INPUT ARRAY INTO INITIAL POSITIONS

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      KLB=KSB
      IF(LOT.LE.0) KLR=KSB+LOT
      DO 90 IL=1,8
      DO 90 KIB=1,KLB
90      TRDATA(KIB,IL)=TRDATA(16+KIB,IL)
C***IF ON LAST INPUT BLOCK OF SECTION 2, FILL REMAINDER WITH ZERO AND
C***WRITE TO DK0
      IF(LOT.GT.0) GO TO 60
      IF(KSB.EQ.16) GO TO 140
100      IF((KIB-16).EQ.1) GO TO 120
      DO 110 IL=1,8
      DO 110 KIL=KIB,16
110      TRDATA(KIL,IL)=0.0
120      WRITE(10,'IFBLK') ((TRDATA(KIL,IL),IL=1,8),KIL=1,16)
140      CALL CLOSE(10)
      CALL CLOSE(11)
      GO TO 180
C***IF ON FIRST SECTION 2 DATA, FILL INITIAL OUTPUT ARRAY POSITIONS
150      IF(KSB.EQ.16) GO TO 80
      DO 160 IL=1,8
      DO 160 KIL=1,KSB
160      TRDATA(KIL,IL)=CODATA(16-KSB+KIL,IL)
      KFIRST=0
      KS=1
      LS=16
      GO TO 60
C***INSURE CORRECT NUMBER OF SAMPLES WRITTEN TO DISC
180      NSAMP2=(IFBLK-ISBLK)*16+(KIB-1)
      WRITE(10D,2010) ILOT,NSAMP2
D      WRITE(10D,2030)
D      READ(1KB,1010) IY1
D      IF(IY1.NE.IYES) STOP 'DATA TRANSFER HALTED'
C***SET PRINTED OUTPUT FLAG
      IY2=IYFS                      !SET TO ALWAYS PRINT
      IF(IY2.NE.IYES) GO TO 270
      WRITE(8,2060)
      WRITE(8,2070) IR(1),ISUB(1),IHOS(1),ITST(1),IPOS(1)
      WRITE(8,2170) ISBLK,IFBLK,((KIB-1)*8),NSAMP2
C***RELOAD INDACC WITH CORRECT INFORMATION
270      ISBL(1)=ISBLK
      IFBL(1)=IFBLK
      KEND(1)=(KIB-1)*8
      DO 280 J=2,3
      ISBL(J)=0
      IFBL(J)=0
280      KEND(J)=0
C***WRITE INDACC TO DISC FILE
      CALL ASSIGN(12,'SY:INDACC.DAT;1')
      DEFINE FILE 12(1,30,U,IF19)
      WRITE(12,'IPOS(1)') IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,
1      TSAMP
      CALL CLOSE(12)
      CALL CLOSE(8)
      CALL EXIT
1000      FORMAT(I4)
1010      FORMAT(A2)
1020      FORMAT(2F15.7)
1030      FORMAT(4I4)
2000      FORMAT(20X,'DATA TRANSFER'/10X,
1      'ENTER KEND(1),KEND(2),ISBL(2),IFBL(2)')
2010      FORMAT(10X,'INPUT',2X,I4,' SAMPLES',5X,'OUTPUT',2X,I4,
1      ' SAMPLES')
2020      FORMAT(10X,'OUTPUT CODATA BLOCK',I4,2X,'THRU BLOCK',I4)
2030      FORMAT(10X,'DOES IT LOOK OK? (YES/NO)')
2040      FORMAT(10X,'WANT TRANSFER STATEMENT PRINTED?(YES/NO)')
2060      FORMAT('1',19X,'DATA TRANSFER TO CODATB.DAT COMPLETED')

```

```
2070  FORMAT(1H , 'RECORD NUM:', I3, 5X, 'SUBJECT NUM:', I3, 5X,  
1      'HOSP NUM:', I6, 5X, 'TEST NUM:', I6, 5X, 'POSITION', I3 / )  
2170  FORMAT(1H , 'FIRST BLOCK:', I4, 2X, 'LAST BLOCK:', I4, 2X,  
1      'LAST WORD:', I4, 2X, 'NUM. OF SAMPLES:', I4)  
2200  FORMAT(10X, 'DATA SECTIONING' / 5X,  
1      'ENTER WALKING SECTION START AND STOP TIMES')  
2210  FORMAT(10X, 'COMPUTED: START TIME=', G14.6, 2X, 'STOP TIME=',  
1      G14.6)  
2220  FORMAT(1H , 'FIRST BLOCK:', I4, 2X, 'LAST BLOCK:', I4, 2X,  
1      'LAST WORD', I4)  
2240  FORMAT(5X, 'ECHO CHECK: ', 4I4)  
      END
```

```

C**** PROGRAM SPEDIT
C*** THIS PROGRAM ITERATES TO PRODUCE AN OMEGA VECTOR WITH MEANS
C***OF APPROXIMATELY ZERO(<TOL). IT USES SUBROUTINE VERSIONS OF
C***COOMEG AND MEANIT CALLED SPOMEG AND SPMEAN.
C***
C*** TASK BUILD AS:
C*** SPEDIT=SPEDIT,SPOMEG,AM3INM,DIOMGM,SPMEAN,[[1,1]F4POTS/LB
C*** UNITS=14 MAXBUF=512
      DIMENSION SMEAN(3,3)
      COMMON/PARAM/IKB,IOD,IPOST,IPOS(3),IR(3),ISUB(3),IHOS(3),
1 ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3),ADJ(4),ADSL(4),
2 ASTR(8),IY1
      COMMON Y(37,4),DY(36,4),CODATA(36,4)
      COMMON /ASV/ID1,ID2,ID3,ID4
      DATA IYES/'YE'/,INO/'NO'/
      CALL ASSIGN(8,'SY:PRNTIT,LST;1')
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
      IY1=INO
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(IOD,2800)
2800 FORMAT(10X,'SPEEDY ITERATION OF OMEGA')
      IPOST=1 !SET FOR POSITION 1 ONLY
      TOL=0.00001 !ITERATION TOLERANCE
      MAXI=40 !MAX NUMBER OF ITERATIONS
      DO 10 I=1,4
10 ADSL(I)=0.0
      D WRITE(IOD,2810)
2810 FORMAT(10X,'ENTER CODATA SLOPE CORRECTIONS=1,2,3,4')
      D READ(IKB,1510) ADSL
1510 FORMAT(4F15.7)
      KOUNT=0
C***SET OFFSET ADJUSTMENTS TO ZERO
      DO 20 I=1,4
20 ADJ(I)=0.0
C***INTEGRATE TO FIND OMEGA VECTOR
40 CALL SPOMEG
C***COMPUTE THE OFFSET CORRECTOR FACTOR SO THAT OFFSETS ARE ADJUSTED
C***BY A FACTOR OF MEAN VALUE X 2 /RUN TIME.
      IF(KOUNT.NE.0) GO TO 50
      RNT=FLUAT((IFBL(2)-ISBL(2))*32+KEND(2)/4)*TSAMP(2)*0.001
      FCT=2.0/RNT
C***COMPUTE MEAN OF OMEGA VECTOR
50 CALL SPMEAN
      KOUNT=KOUNT+1
      WRITE(IOD,2820) (ASTR(1),I=1,4)
2820 FORMAT(2X,'MEANS=',4(2X,G14.7))
      IF(KOUNT.GT.MAXI) STOP 'TOO MANY ITERATIONS'
C***ITEPATE ON OMEGA(2) UNTIL LESS THAN TOLERANCE BY ADJUSTING
C*** CODATA(2)
      IF(ABS(ASTR(2)).LE.TOL) GO TO 60
      ADJ(2)=ADJ(2)+FCT*ASTR(2)
      GO TO 40
C***AFTER OMEGA(2) MEAN LESS THAN TOLERANCE ADJUST CODATA(1) AND (3)
60 IF(ABS(ASTR(1)).LE.TOL.AND.ABS(ASTR(3)).LE.TOL) GO TO 100
      ADJ(1)=ADJ(1)-FCT*ASTR(1)
      ADJ(3)=ADJ(3)+FCT*ASTR(3)
      GO TO 40
100 IF(IY1.EQ.IYES) GO TO 120
      IY1=IYES
      GO TO 40
C***STORE MEAN DATA FOR OMEGA IN SMEAN(1,2)

```

```
120      CALL ASSIGN(14,'SY:STMEAN.DAT;1',16)
        DEFINE FILE 14(1,18,U,IGUESS)
        CALL FDBSET(14,'NEW')
        DO 140 I=1,3
140      SMEAN(1,I)=ASTR(I)
        WRITE(14'IPOST) ((SMEAN(J,I),I=1,3),J=1,3)
        CALL CLOSE(14)
        CALL CLOSE(8)
        CALL EXIT
        END
```

```

      SUBROUTINE SPOMEG
C***      PROGRAM COOMEG
C***  THIS PROGRAM INTEGRATES THE DIFFERENCE DATA STORED IN
C***SY:CODATB.DAT TO PRODUCE THE THREE COMPONENTS OF THE ROTATION
C***VECTOR OMEGA.  IT STORES
C***OMG1,OMG2,OMG3, AND MEAN SQUARE INTEGRATION ERROR ON DISC FILE
C***SY:OMEGA.DAT. THE INDEX TO SY:OMEGA.DAT IS STORED IN ARRAY
C***POSITION (2) OF INDEX FILE SY:INDACC.DAT.
      COMMON /PARAM/IKB,IOD,IPOST,IPOS(3),IR(3),ISUB(3),IHOS(3),
1      ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3),ADJ(4),ADSL(4),
2      ASTR(8),IY1
      COMMON Y(37,4),DY(36,4),CODATA(36,4)
      COMMON /ASV/IF15,IF17,IF19,ID4
      DIMENSION STDATA(36,8)
      EXTERNAL DIOMGM
      DATA IYES/'YE'/
C***ASSIGN AND DEFINE OUTPUT FILES
      CALL ASSIGN(9,'SY:OMEGA.DAT;1')
      DEFINE FILE 9(65,256,U,IF15)
C***READ POINTER INDEX FILE
      CALL ASSIGN(10,'SY:INDACC.DAT;1')
      DEFINE FILE 10(1,30,U,IF19)
      CALL FDBSET(10,'READONLY')
      READ(10'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
      IRLK=ISBL(1)      !INPUT BLOCK INDEX
      IOBLK=1           !OUTPUT BLOCK INDEX
      IF(IPOST.EQ.2) IOBLK=IOBLK+65
      IF(IPOST.EQ.3) IOBLK=IOBLK+130
      ISBL(2)=IOBLK
C***SET INITIAL VALUES FOR ENTRY INTO INTEGRATION ROUTINE AM3INM
C***N.B.:OMEGA AND OMEGADOT SET TO ZERO
      DO 10 I=1,4
      DO 10 J=1,4
      Y(J,I)=0.0
10      DY(J,I)=0.0
      LOT=16*(IFBL(1)-ISBL(1))+KEND(1)/8
      H=TSAMP(1)*0.001
C***ENTER CODATA OFFSETS(ONLY POSITIONS 1-4)
      D      WRITE(IOD,2010)
2010      FORMAT(5X,'ENTER CODATA OFFSETS--POSITIONS 1,2,3,4 ONLY')
      D      READ(IKB,1020) (ADJ(I),I=1,4)
1020      FORMAT(4F15.7)
      D      WRITE(IOD,2060)
2060      FORMAT(5X,'ENTER CODATA SLOPE CORRECTIONS--1,2,3,4')
      D      READ(IKB,1020) (ADSL(I),I=1,4)
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(11,'SY:CODATB.DAT;1')
      DEFINE FILE 11(130,256,U,IF12)
      CALL FDBSET(11,'READONLY')
C***READ IN TWO BLOCKS OF INPUT DATA
C***SET SAMPLE INDEX FOR FIRST BLOCK
20      LS=20           !4 IC'S + 16 SAMPLES
C***IF ON LAST INPUT BLOCK,REDUCE LS
      IF(IBLK.EQ.IFBL(1)) LS=(KEND(1)/8)+4
      READ(11'IBLK) ((STDATA(KI,I),I=1,8),KI=5,LS)
      IBLK=IBLK+1
C***IF LAST INPUT BLOCK WAS READ,JUMP TO DATA TRANSFER
      IF(IBLK.GT.IFBL(1)) GO TO 30
      LS=36
      IF(IBLK.EQ.IFBL(1)) LS=(KEND(1)/8)+20
C***READ IN SECOND INPUT DATA BLOCK

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      READ(11'IBLK) ((STDATA(KI,I),I=1,6),KI=21,LS)
      IBLK=IBLK+1
C***TRANSFER INPUT DATA TO INTEGRATION ARRAY
30    DO 40 KI=5,LS
      T=FLOAT((IBLK-ISBL(1)-1)*16+(KI-5))*H
      DO 40 I=1,4
40    CODATA(KI,I)=STDATA(KI,I)-ADJ(1)-ADSL(I)*T
C***INTEGRATE BLOCK OF DATA
C***
      CALL AM3INM(DIOMGM,H,LS)
C***
C***IF ON LAST BLOCK,STORE ZERO IN REMAINDER
      IF(IBLK.LT.IFBL(1)) GO TO 60
      LOS=LS+1
      IF(LOS.GT.36) GO TO 60
      DO 50 J=LOS,36
      DO 50 I=1,4
50    Y(J,I)=0.0
C***WRITE INTEGRATED BLOCK TO DISC FILES AND INDEX BLOCK
60    WRITE(9'IOBLK) ((Y(KI,I),I=1,4),KI=5,36)
      IOBLK=IOBLK+1
C***TEST FOR END OF DATA
      IF(IBLK.GT.IFBL(1)) GO TO 80
C***RESET ARRAYS WITH INITIAL CONDITIONS FOR NEXT DATA BLOCK
      DO 70 I=1,4
      DO 70 J=1,4
      Y(J,I)=Y(J+32,I)
      DY(J,I)=DY(J+32,I)
70    CODATA(J,I)=CODATA(J+32,I)
      GO TO 20
C***CLOSE ALL OPEN FILES
80    CALL CLOSE(9)
      CALL CLOSE(11)
C***COMPUTE LAST WORD INTEGRATED AND LAST BLOCK WRITTEN TO DISC
      KEND(2)=(LS-4)*4
      IFBL(2)=IOBLK-1
C***WRITE ON TX INFORMATION ON INTEGRATED DATA
D    WRITE(10D,2020) IR(2),ISUB(2),IHOS(2),ITST(2),IPOST
2020  FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
      1  'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION',I3)
D    WRITE(10D,2090) ISBL(1),IFBL(1),KEND(1)
D    WRITE(10D,2090) ISBL(2),IFBL(2),KEND(2)
D    WRITE(10D,2050) (ADJ(I),I=1,4)
2050  FORMAT(1H,'DATA ADJUSTED USING:',/5X,'OFFSETS:',4(X,G14.7))
D    WRITE(10D,2080) (ADSL(I),I=1,4)
2080  FORMAT(5X,'SLOPES:',4(X,G14.7))
C***IF DATA LOOKS GOOD--STORE INDEX INFO AND CARRY ON
D    WRITE(10D,2030)
2030  FORMAT(10X,'DOES IT LOOK OK? (YES/NO)')
D    READ(1KB,1010) IY
D    IF(IY.NE.IYES) STOP 'INTEGRATION ABORTED'
C***STORE NEW INDEXING INFORMATION
      CALL ASSIGN(13,'SY:INDACC.DAT;1')
      DEFINE FILE 13(1,30,U,IF19)
      WRITE(13'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(13)
C***TEST PRINTED OUTPUT FLAG
      IF(IY1.NE.IYES) GO TO 100
      WRITE(8,2070)
2070  FORMAT(1H,19X,'OMEGA INTEGRATION COMPLETED ON'/)
      WRITE(8,2020) IR(2),ISUB(2),IHOS(2),ITST(2),IPOST
      WRITE(8,2090) ISBL(2),IFBL(2),KEND(2)
2090  FORMAT(1H,'INITIAL BLOCK:',I4,2X,'FINAL BLOCK:',I4,2X,
      1  'LAST WORD:',I4)
      WRITE(8,2050) (ADJ(I),I=1,4)
      WRITE(8,2080) (ADSL(I),I=1,4)

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      SUBROUTINE AM3INM(DIFUN,H,L)
C***  THIS SUBROUTINE INTEGRATES 3 FIRST ORDER DIFF EOS
C***USING A 4TH ORDER ADAMS-BASHFORTH-MOULTON METHOD
C***  BEFORE ENTRY THE FIRST 4 POSITIONS IN ARRAYS Y AND
C***DY MUST BE LOADED WITH THE INITIAL VALUES AND THE VALUES
C***FOR THE NEXT 3 STEPS CORRESPONDING TO:
C***      TI      T1      T2      T3
C***      Y(1,I)   Y(2,I)   Y(3,I)   Y(4,I)
C***      DY(1,I)   DY(2,I)   DY(3,I)   DY(4,I)
C***  PARAMETER DESCRIPTIONS:
C***  ARRAY Y: INDEPENDENT VARIABLES IN Y(L,1),Y(L,2),Y(L,3)
C***            MEAN SQ DIFF BETWEEN PREDICTOR AND CORRECTOR
C***            IN Y(L,4)
C***  ARRAY DY: DERIVATIVES OF INDEPENDENT VARIABLES IN DY(L,1),
C***            DY(L,2),DY(L,3). DY(L,4) IS NOT FILLED BY THIS
C***            SUBROUTINE
C***  H: STEP SIZE(NORMALLY IN SECONDS)
C***  L: TOTAL STEPS TO BE COMPLETED FROM TI NOT TO EXCEED 36
      DIMENSION A(4),B(4),EPR(3)
      COMMON Y(37,4),DY(36,4),CUDATA(36,4)
C***COMPUTE AND STORE COEFFICIENTS
      A(1)=H*2.291667
      A(2)=-H*2.458333
      A(3)=H*1.541667
      A(4)=-H*0.375
      B(1)=H*0.375
      B(2)=H*0.7916667
      B(3)=-H*0.2083333
      B(4)=H*0.04166667
C***BEGIN OVERALL INTEGRATION LOOP
      DO 30 J=5,L
C***COMPUTE PREDICTOR AND STORE IN Y(J+1,I)
      DO 10 I=1,3
10      Y(J+1,I)=Y(J-1,I)+A(1)*DY(J-1,I)+A(2)*DY(J-2,I)
          1  +A(3)*DY(J-3,I)+A(4)*DY(J-4,I)
C***COMPUTE DY USING PREDICTOR
      CALL DIFUN(J+1,J)
C***COMPUTE CORRECTOR
      DO 20 I=1,3
          Y(J,I)=Y(J-1,I)+B(1)*DY(J,I)+B(2)*DY(J-1,I)
          1  +B(3)*DY(J-2,I)+B(4)*DY(J-3,I)
20      ERR(I)=ABS(Y(J,I)-Y(J+1,I))
C***COMPUTE DY USING CORRECTOR
      CALL DIFUN(J,J)
30      Y(J,4)=SQRT(ERR(1)**2+ERR(2)**2+ERR(3)**2)
      RETURN
      END

```

```
      SUBROUTINE DIOMGM(LY,LDY)
C***THIS SUBROUTINE CONTAINS THE DIFFERENTIAL EQUATIONS
C*** WHICH DEFINE THE SOLUTION TO THE ROTATION VECTOR OMEGA
      COMMON Y(3,,4),DY(36,4),CODATA(36,4)
      DY(LDY,1)=Y(LY,2)*Y(LY,3)-CODATA(LDY,1)
      DY(LDY,2)=CODATA(LDY,2)
      DY(LDY,3)=-Y(LY,1)*Y(LY,2)+CODATA(LDY,3)
      RETURN
      END
```

```

      SUBROUTINE SPMEAN
C***      PROGRAM MEANIT
C***      THIS PROGRAM COMPUTES THE MEANS OF SY:OMEGA.DAT
      COMMON/PARAM/IKR,IOD,IPOST,IPOS(3),IR(3),ISUB(3),IHOS(3),
1      ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3),ADJ(4),ADSL(4),
2      ASTR(8),IY1
      COMMON /ASV/IF15,IF17,IF19,IF24
      DIMENSION CDATA(32,8)
      DATA IYES/'YE'/
C***OPEN INPUT FILE AND SET PARAMETER VALUES
      CALL ASSIGN(12,'SY:OMEGA.DAT;1')
      DEFINE FILE 12(65,256,U,IF15)
      CALL FDBSET(12,'READONLY')
      IFILE=12
      IPL=2
      IL=4
      KIL=32
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(IPL)
      LS=KIL
      LOT=LS*(IFBL(IPL)-ISBL(IPL))+KEND(IPL)/IL
      H=TSAMP(1)*0.001
C***ZERO SUMMING LOCATIONS
      DO 10 I=1,IL
10      ASTR(I)=0.0
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20      READ(IFILE'IBLK) ((CDATA(KI,I),I=1,IL),KI=1,KIL)
      IBLK=IBLK+1
C***COMPUTE SUM OF ALL SAMPLES AND STORE
      DO 30 KI=1,KIL
      DO 30 I=1,IL
30      ASTR(I)=CDATA(KI,I)+ASTR(I)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
      IF(IBLK.EQ.IFBL(IPL)) LS=KEND(IPL)/IL
C***TEST FOR END OF INPUT DATA
      IF(IBLK.GT.IFBL(IPL)) GO TO 40
      GO TO 20
C***CLOSE OPEN FILE
40      CALL CLOSE(IFILE)
C***COMPUTE MEAN VALUE
      DO 50 I=1,IL
50      ASTR(I)=ASTR(I)/FLOAT(LOT)
      IF(IY1.NE.IYES) GO TO 80
      WRITE(8,2310)
2310      FORMAT(15X,'FOR FILE SY:OMEGA.DAT;1')
      WRITE(8,2100) IR(IPL),ISUB(IPL),IHOS(IPL),ITST(IPL),IPOST
2100      FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1      'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
      WRITE(8,2110) ISBL(IPL),IFBL(IPL),KEND(IPL),LOT
2110      FORMAT(1H,'FIRST BLOCK:',I4,2X,'LAST BLOCK:',I4,2X,
1      'LAST WORD:',I4,2X,'NUM. OF SAMPLES:',I4)
      WRITE(8,2030) (ASTR(I),I=1,IL)
2030      FORMAT(10X,'MEAN(1),(2),.....=',/4G15.7,/4G15.7/)
80      RETURN
      END

```

```

C***      PROGRAM OMGFIL
C***      THIS PROGRAM FILTERS DATA IN SY:OMEGA.DAT USING AN 8TH ORDER
C***RECURSIVE BUTTERWORTH FILTER. THE DATA IN SY:OMEGA.DAT IS
C***REPLACED BY THE FILTERED DATA.
C***
C***      TASK BUILD AS: OMGFIL=OMGFIL,RNDPAS,[1,1]F4POTS/LB
C***      UNITS=10                      MAXHUF=512
C***      DIMENSION CODATA(32,4),SIDATA(2000),IPOS(3),IR(3),ISUP(3)
C***      DIMENSION IHOS(3),ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3)
C***      COMMON /ASV/IF22,IF19
C***      DATA IYES/'YE'/
C***      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
C***      CALL FDBSET(8,'APPEND')
C***      IKB=5
C***      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
C***      WRITE(100,2000)
2000      FORMAT(20X,'OMEGA FILTERING')
C***      IPOST=1          !SET POSITION 1 ONLY
C***ASSIGN AND DEFINE INPUT/OUTPUT FILE
C***      CALL ASSIGN(9,'SY:OMEGA.DAT;1',16)
C***      DEFINE FILE 9(65,256,U,IF22)
C***      CALL FDBSET(9,'OLD')
C***READ POINTER INDEX FILE
C***      CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
C***      DEFINE FILE 10(1,30,U,IF19)
C***      CALL FDBSET(10,'READONLY')
C***      READ(10'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
C***      CALL CLOSE(10)
C***ENTER LOWER AND UPPER BANDPASS FREQUENCIES
C***      FC1=0.50          !LOWER SET TO 0.50 HZ
C***      FC2=10.0         !UPPER SET TO 10.0 HZ
C***SET INITIAL INDEX VALUES
C***      IBLK=ISBL(2)
C***      LS=32
C***      LOT=LS*(IFBL(2)-ISBL(2))+KEND(2)/4
C***      FS=1000.0/TSAMP(2)
C***      II=1
C***LOAD ALL SAMPLES OF CODATA(-,1) INTO SIDATA
10      READ(9'IBLK) ((CODATA(KI,I),I=1,4),KI=1,LS)
C***      IBLK=IBLK+1
C***      DO 20 KB=1,LS
C***          IND=(IBLK-ISBL(2)-1)*32+KB
20      SIDATA(IND)=CODATA(KB,II)
C***      IF(IBLK.EQ.IFBL(2)) LS=KEND(2)/4
C***      IF(IBLK.GT.IFBL(2)) GO TO 40
C***      GO TO 10
C***INCREMENT ARRAY POSITION AND IF LAST POSITION FILTERED EXIT LOOP
30      II=II+1
C***      IF(II.GT.3) GO TO 90
C***FILTER ONE ARRAY POSITION OF DATA(STORED IN SIDATA)
40      CALL RNDPAS(SIDATA,LOT,FC1,FC2,FS)
C***RESET BLOCK AND WORD INDEXES
C***      IBLK=ISBL(2)
C***      LS=32
C***RELOAD CODATA TO REPLACE FILTERED ARRAY POSITION AND TO
C***LOAD SIDATA WITH NEXT APRAY POSITION TO BE FILTERED
50      READ(9'IBLK) ((CODATA(KI,I),I=1,4),KI=1,LS)
C***      IOBLK=IBLK
C***      IRLK=IBLK+1
C***      DO 60 KB=1,LS
C***          IND=(IOBLK-ISBL(2))*32+KB
C***LOAD FILTERED DATA INTO CODATA

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        CODATA(KB,II)=SIDATA(IND)
        IF(II.GE.4) GO TO 60
C***LOAD NEXT ARRAY POSITION TO BE FILTERED INTO SIDATA
        SIDATA(IND)=CODATA(KB,II+1)
60      CONTINUE
C***WRITE FILTERED DATA TO DISC FILE
        WRITE(9'IOBLK) ((CODATA(KI,I),I=1,4),KJ=1,LS)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
        IF(IBLK.EQ.IFBL(2)) LS=KEND(2)/4
C***TEST FOR END OF INPUT DATA
        IF(IBLK.GT.IFPL(2)) GO TO 30
        GO TO 50
C***CLOSE OPEN FILE
90      CALL CLOSE(9)
C***WRITE ADJUSTMENT INFO ON TERMINAL SCREEN
        WRITE(10D,2030)
2030     FORMAT(10X,'OMEGA FILTERING COMPLETED ON:')
        WRITE(10D,2060) IR(1),ISUR(1),IHOS(1),ITST(1),IPOS(1)
2060     FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1        'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I4)
        WRITE(10D,2070) FC1,FC2
2070     FORMAT(10X,'BANDPASS FREQUENCIES:',F9.2,' TO',F9.2,' HZ')
        KENDR=(KI-1)*4
        WRITE(10D,2110) ISBL(2),IOBLK,KENDR,LOT
C***SET PRINTED OUTPUT FLAG
        IY1=IYES          !SET TO ALWAYS PRINT
        IF(IY1.NE.IYES) GO TO 100
        WRITE(8,2030)
        WRITE(8,2060) IR(1),ISUR(1),IHOS(1),ITST(1),IPOS(1)
        WRITE(8,2070) FC1,FC2
        WRITE(8,2110) ISBL(2),IOBLK,KENDR,LOT
2110     FORMAT(1H,'FIRST BLOCK:',I4,2X,'LAST BLOCK:',I4,2X,
1        'LAST WORD:',I4,2X,'NUM. OF SAMPLES:',I4)
100     CALL CLOSE(8)
        CALL EXIT
        END

```

```

C***      PROGRAM INANGL
C***      THIS PROGRAM COMPUTES THE INITIAL ANGLES THETA AND
C***PHI FROM PAIR MEAN VALUES AND STORES THEM ON DISC FILE
C***SY:STRANG.DAT. HETA IS SET TO ZERO DEGRFES.
C***
C***      TASK BUILD AS: INANGL=INANGL,[1,1]F4POTS/LB
C***      UNITS=10      MAXRUF=512
      DIMENSION V(5),STATS(6,16)
      COMMON /ASV/IF20,IF30
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
      RADEG=57.29577951
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(100,2000)
2000      FORMAT(20X,'INITIAL ANGLE COMPUTATION')
      IPOST=1      !SET POSITION 1 ONLY
C***LOAD PMV'S FROM STATISTICS DISC FILE
      CALL ASSIGN(9,'SY:COSTAT.DAT;1',16)
      DEFINE FILE 9(3,192,U,IF20)
      CALL FDBSET(9,'READONLY')
      ISEC=1
      READ(9'ISEC) ((STATS(IS,JS),IS=1,6),JS=1,16)
      CALL CLOSE(9)
      V(1)=STATS(6,1)
      V(2)=STATS(6,3)
      V(3)=STATS(6,5)
      V(4)=STATS(6,7)
C***WRITE OUT PMV'S ON TERMINAL SCREEN
      WRITE(100,2050) (V(I),I=1,4)
2050      FORMAT(1H,'PMV 1,3,5,7: ',4(2X,F12.7))
C***COMPUTE MEAN OF PMV(3) AND PMV(5)
      V(5)=(V(2)+V(3))*0.5
      MAX=50      !MAX NUM OF ITERATIONS
      TOL=0.0035      !TOLERANCE= 0.2 DEG-S
      KOUNT=0
      Q=V(1)*V(1)/V(5)/V(5)
      SPH=-V(5)
      CPH=SQRT(1.0-SPH*SPH)
10      CS2TR=V(4)*V(4)+Q*SPH*SPH*CPH*CPH
      IF(CS2TR.GT.1.0) STOP 'COS PHI GT 1.0'
      PH1=ATAN2(SPH,CPH)
2010      FORMAT(2(2X,G14.7))
      SI2TR=SQRT(1.0-CS2TR)
      PH2=ATAN2(SI2TR,SQRT(CS2TR))
      IF(PH1.LT.0.0) PH2=-PH2
      DEL=PH2-PH1
D      WRITE(100,2010) PH1,DEL
      IF(ABS(DEL).LT.TOL) GO TO 20
      SPH=SIN(PH1+DEL)
      CPH=SQRT(1.0-SPH*SPH)
      KOUNT=KOUNT+1
      IF(KOUNT.GT.MAX) STOP 'EXCEEDED 50 ITERATIONS'
      GO TO 10
20      CTH=-V(4)/CPH
      STH=SQRT(1.0-CTH*CTH)
      IF(V(1).LT.0.0) STH=-STH
      THETA=ATAN2(STH,CTH)*RADEG
      BETA=0.0
      PHI=PH1*RADEG
      PMV1=STH*CBTA

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      PMV35=-SPH*CHTA
      PMV7=-CPH*CTH
      WRITE(10D,2020) THETA,PHI,BETA,PMV1,PMV35,PMV7
2020  FORMAT(5X,'THETA=',G14.7,2X,'PHI=',G14.7,2X,'BETA=',G14.7,
      1  /,5X,'PMV1=',G14.7,2X,'PMV35=',G14.7,2X,'PMV7=',G14.7)
C***WRITE ANGLES TO DISC FILE
      CALL ASSIGN(10,'SY:STRANG.DAT;1',16)
      DEFINE FILE 10(1,6,U,IF30)
      CALL FDBSET(10,'NEW')
      WRITE(10'IPOS1) THETA,PHI,BETA
      CALL CLOSE(10)
C***SET PRINTED OUTPUT FLAG
      IY=IYES !SET TO ALWAYS PRINT
      IF(IY.NE.IYES) GO TO 100
      WRITE(8,2040) (V(I),I=1,4)
2040  FORMAT(1H,10X,'INITIAL ANGLES COMPUTED FOR:',/5X,'PMV(1)=' ,
      1  G14.7,2X,'PMV(3)=' ,G14.7,2X,'PMV(5)=' ,G14.7,2X,'PMV(7)=' ,
      2  G14.7)
      WRITE(8,2020) THETA,PHI,BETA,PMV1,PMV35,PMV7
100   CALL CLOSE(8)
      CALL EXIT
      END

```

```

C***      PROGRAM COANGL
C***      THIS PROGRAM INTEGRATES THE OMEGA VECTOR STORED IN
C***SY:OMEGA.DAT TO PRODUCE THE THREE ROTATION ANGLES(THETA,
C***PHI AND BETA). IT STORES THETA, PHI AND BETA
C***AND MEAN SQUARE INTEGRATION ERROR ON DISC FILE
C***SY:ANGLES.DAT. THE INDEX TO SY:ANGLES.DAT IS STORED
C***IN ARRAY POSITION (2) OF INDEX FILE SY:INDACC.DAT.
C***
C***      TASK BUILD AS  COANGL=COANGL,AM3INM,DIANGL,[1,1]F4POTS/LB
C***                      UNITS=12          MAXBUF=512
      DIMENSION IPOS(3),IR(3),ISUB(3),IHOS(3),ITST(3)
      DIMENSION ISBL(3),IFBL(3),KEND(3),TSAMP(3),ADJ(3),ADSL(3)
      COMMON Y(37,4),DY(36,4),CODATA(36,4)
      COMMON /ASV/IF15,IF24,IF19,IF30
      EXTERNAL DIANGL
      DATA IYES/'YF'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(100,2000)
2000      FORMAT(20X,'ROTATION ANGLE INTEGRATION')
      IPOST=1          !SET POSITION 1 ONLY
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(9,'SY:OMEGA.DAT;1',15)
      DEFINE FILE 9(65,256,U,IF15)
      CALL FDBSET(9,'READONLY')
C***READ POINTER INDEX FILE
      CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
      DEFINE FILE 10(1,30,U,IF19)
      CALL FDBSET(10,'READONLY')
      READ(10'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(2)      !INPUT BLOCK INDEX
      IOBLK=ISBL(2)     !OUTPUT BLOCK INDEX
C***SET INITIAL VALUES FOR ENTRY INTO INTEGRATION ROUTINE AM3INM
C***READ INITIAL ANGLE VALUES FROM DATA FILE
      CALL ASSIGN(11,'SY:STRANG.DAT;1',16)
      DEFINE FILE 11(1,6,U,IF30)
      CALL FDBSET(11,'READONLY')
      READ(11'IPOST) THETA1,PHI1,BETA1
      CALL CLOSE(11)
      RADEG=57.29577951
C***N.B.: ANGLEDEG'S SET TO ZERO
      DO 10 I=1,4
          Y(I,1)=THETA1/RADEG
          Y(I,2)=PHI1/RADEG
          Y(I,3)=BETA1/RADEG
          Y(I,4)=0.0
      DO 10 J=1,4
10          DY(I,J)=0.0
          LS=36
          LUT=16*(IFBL(2)-ISBL(2))+KEND(2)/8
          H=TSAMP(2)*0.001
C***ENTER OMEGA OFFSETS AND SLOPE CORRECTIONS
      DO 15 J=1,3
          ADJ(J)=0.0
15          ADSL(J)=0.0
      D          WRITE(100,2010)
2010      FORMAT(5X,'ENTER OMEGA OFFSETS--POSITIONS 1,2,3 ONLY')
      D          READ(100,2020) (ADJ(I),I=1,3)

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1020    FORMAT(3F15.7)
D      WRITE(JOD,2015)
2015    FORMAT(5X,'ENTER OMEGA SLOPE CORRECTIONS--1,2,3')
D      READ(IKB,1020) (ADSL(I),I=1,3)
C***ASSIGN AND DEFINE OUTPUT FILE
      CALL ASSIGN(12,'SY:ANGLFS.DAT;1',16)
      DEFINE FILE 12(65,256,U,IF24)
      CALL FDBSET(12,'NEW')
C***PEAD IN BLOCK OF INPUT DATA AND INDEX BLOCK
20      READ(9'IBLK) ((CODATA(KI,I),I=1,4),KI=5,LS)
      IBLK=IBLK+1
C***ADJUST OMEGA INPUT DATA FOR OFFSET AND SLOPE
      DO 30 KI=5,LS
      T=FLOAT((IBLK-ISBL(2)-1)*32+(KI-5))*H
      DO 30 I=1,3
30      CODATA(KI,I)=CODATA(KI,I)-ADSL(I)*T-ADJ(I)
C***INTEGRATE BLOCK OF DATA
C***
      CALL AM3INH(DIANGL,H,LS)
C***
C***IF ON LAST BLOCK,STORE ZERO IN REMAINDER
      IF(IBLK.LT.IFBL(2)) GO TO 60
      LOS=LS+1
      IF(LOS.GT.36) GO TO 60
      DO 50 J=LOS,36
      DO 50 I=1,4
50      Y(J,I)=0.0
C***CONVERT ANGLES FROM RADIANS TO DEGREES
60      DO 65 J=5,36
      DO 65 I=1,4
65      Y(J,I)=Y(J,I)*RADEG
C***WRITE INTEGRATED BLOCK TO DISC FILES AND INDEX BLOCK
      WRITE(12'IOBLK) ((Y(KI,I),I=1,4),KI=5,36)
      IOBLK=IOBLK+1
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD + 4
      IF(IOBLK.EQ.IFBL(2)) LS=(KEND(2)/4)+4
C***TEST FOR END OF DATA
      IF(IBLK.GT.IFBL(2)) GO TO 80
C***RESET ARRAYS WITH INITIAL CONDITIONS FOR NEXT DATA BLOCK
      DO 70 I=1,4
      DO 70 J=1,4
      Y(J,I)=Y(J+32,I)/RADEG
      DY(J,I)=DY(J+32,I)
70      CODATA(J,I)=CODATA(J+32,I)
      GO TO 20
C***CLOSE ALL OPEN FILES
80      CALL CLOSE(9)
      CALL CLOSE(12)
C***COMPUTE LAST WORD INTEGRATED AND LAST BLOCK WRITTEN TO DISC
      KEND(2)=(LS-4)*4
      IFBL(2)=IOBLK-1
C***WRITE ON TERMINAL SCREEN INFORMATION ON INTEGRATED DATA
      WRITE(IOD,2020) IP(2),ISUB(2),IHOS(2),ITST(2),IPOST
2020    FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1      'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION',I3)
      WRITE(IOD,2090) ISBL(2),IFBL(2),KEND(2)
      WRITE(JOD,2100) THETA1,PHI1,BETA1
2100    FORMAT(1H,5X,'INITIAL ANGLES:',3(2X,G12.5))
      WRITE(IOD,2050) (ADJ(I),I=1,3)
2050    FORMAT(1H,'DATA ADJUSTED USING:',3(X,G14.7))
      WRITE(IOD,2060) (ADSL(I),I=1,3)
2060    FORMAT(3X,'SLOPES:',3(X,G14.7))
C***IF DATA LOOKS GOOD--STORE INDEX INFO AND CARRY ON
D      WRITE(IOD,2030)
2030    FORMAT(10X,'DOES IT LOOK OK? (YES/NO)')
D      READ(IKB,1010) IY

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D      IF(IY.NE.IYES) STOP 'INTEGRATION ABORTED'
C***SET PRINTED OUTPUT FLAG
      IY1=IYES                                !SET TO ALWAYS PRINT
      IF(IY1.NE.IYES) GO TO 100
      WRITE(8,2070)
2070   FORMAT(1H ,19X,'ROTATION ANGLE INTEGRATION COMPLETED ON'//)
      WRITE(8,2020) IP(2),ISUB(2),IHOS(2),IIST(2),IPOST
      WRITE(8,2090) ISBL(2),IFBL(2),KEND(2)
      WRITE(8,2100) THETA1,PHI1,BETA1
2090   FORMAT(1H , 'INITIAL BLOCK:',I4,2X,'FINAL BLOCK:',I4,2X,
1       'LAST WORD:',I4)
      WRITE(8,2050) (ADJ(I),I=1,3)
      WRITE(8,2060) (ADSL(I),I=1,3)
100    CALL CLOSE(8)
      CALL EXIT
      END

```

```

      SUBROUTINE DIANGL(LY,LDY)
C***THIS SUBROUTINE CONTAINS THE DIFFERENTIAL EQUATIONS
C*** WHICH DEFINE THE SOLUTION TO THE ROTATION ANGLES
C***THETA,PHI AND BETA. THETA ==ARRAY POS (-,1),
C***PHI ==ARRAY POS(-,2), BETA ==ARRAY POS(-,3).
      COMMON Y(37,4),DY(36,4),CODATA(36,4)
      STH=SIN(Y(LY,1))
      CTH=SQRT(1.0-STH*STH)
      SPH=SIN(Y(LY,2))
      CPH=SQRT(1.0-SPH*SPH)
      TPH=SPH/CPH
      SBT=SIN(Y(LY,3))
      CBT=SQRT(1.0-SBT*SBT)
      DY(LDY,1)=1PH*(STH*CODATA(LDY,1)+CTH*CODATA(LDY,3))+CODATA(LDY,2)
      DY(LDY,2)=CTH*CODATA(LDY,1)-STH*CODATA(LDY,3)
      DY(LDY,3)=(STH*CODATA(LDY,1)+CTH*CODATA(LDY,3))/CPH
      RETURN
      END

```

```

C***      PROGRAM FILANG
C***      THIS PROGRAM FILTERS DATA IN SY:ANGLES.DAT USING AN 8TH ORDER
C***RECURSIVE BUTTERWORTH FILTER. THE FILTERED DATA IS STORED IN
C***DISC FILE SY:NEWANG.DAT.
C***
C***      TASK BUILD AS FILANG=FILANG,RNDPAS,[1,1]F4PTS/LB
C***      UNITS=11      MAXBUF=512
      DIMENSION RFLAT(32,4),SIDATA(2000),IPOS(3),IR(3),ISUB(3)
      DIMENSION IHOS(3),ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3)
      COMMON /ASV/IF15,IF19,IF25
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(IOD,2000)
2000      FORMAT(20X,'ANGLES FILTERING')
      IPOST=1      !SET POSITION 1 ONLY
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(9,'SY:ANGLES.DAT;1',16)
      DEFINE FILE 9(65,256,U,IF15)
      CALL FDBSET(9,'READONLY')
C***ASSIGN AND DEFINE OUTPUT FILE
      CALL ASSIGN(10,'SY:NEWANG.DAT;1',16)
      DEFINE FILE 10(65,256,U,IF25)
      CALL FDBSET(10,'NEW')
C***READ POINTER INDEX FILE
      CALL ASSIGN(11,'SY:INDACC.DAT;1',16)
      DEFINE FILE 11(1,30,U,IF19)
      CALL FDBSET(11,'READONLY')
      READ(11'IPOST) IPOS,IF,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(11)
C***ENTER LOWER AND UPPER BANDPASS FREQUENCIES
      FC1=0.50      !LOWER SET TO 0.50 HZ
      FC2=10.0      !UPPER SET TO 10.0 HZ
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(2)
      LS=32
      LOT=LS*(IFBL(2)-ISBL(2))+KEND(2)/4
      FS=1000.0/TSAMP(2)
      II=1
C***LOAD ALL SAMPLES OF ANGLES(-,1) INTO SIDATA
10      READ(9'IBLK) ((RFLAT(KI,I),I=1,4),KI=1,IS)
C***
C***ON FIRST PASS, LOAD UNFILTERED ANGLES INTO FILE 10
      IF(II.EQ.1) WRITE(10'IBLK) ((RFLAT(KI,I),I=1,4),KI=1,IS)
C***
      IBLK=IBLK+1
      DO 20 KB=1,IS
      IND=(IBLK-ISBL(2)-1)*32+KB
      SIDATA(IND)=RFLAT(KB,II)
      IF(IBLK.EQ.IFBL(2)) LS=KEND(2)/4
      IF(IBLK.GT.IFBL(2)) GO TO 40
      GO TO 10
C***INCREMENT ARRAY POSITION AND IF LAST POSITION FILTERED EXIT LOOP
30      II=II+1
C***      NOTE:DO NOT FILTER ARRAY POSITION 4
      IF(II.GT.3) GO TO 90
C***FILTER ONE ARRAY POSITION OF DATA(STORED IN SIDATA)
40      CALL BNDPAS(SIDATA,LOT,FC1,FC2,FS)
C***RESET BLOCK AND WORD INDEXES
      IBLK=ISBL(2)

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      LS=32
C***RELOAD RFLAT TO REPLACE FILTERED ARRAY POSITION AND TO
C***LOAD SIDATA WITH NEXT ARRAY POSITION TO BE FILTERED
50   READ(10*IBLK) ((RFLAT(KI,I),I=1,4),KI=1,LS)
      IOBLK=IBLK
      IBLK=IBLK+1
      DO 60 KB=1,LS
      IND=(IOBLK-ISBL(2))*32+KB
C***LOAD FILTERED DATA INTO RFLAT
      RFLAT(KB,II)=SIDATA(IND)
      IF(II.GE.4) GO TO 60
C***LOAD NEXT ARRAY POSITION TO BE FILTERED INTO SIDATA
      SIDATA(IND)=RFLAT(KB,II+1)
60   CONTINUE
C***WRITE FILTERED DATA TO DISC FILE
      WRITE(10*IOBLK) ((RFLAT(KI,I),I=1,4),KI=1,LS)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
      IF(JBLK.EQ.IFRL(2)) LS=KEND(2)/4
C***TEST FOR END OF INPUT DATA
      IF(IBLK.GT.IFRL(2)) GO TO 30
      GO TO 50
C***CLOSE OPEN FILES
90   CALL CLOSE(9)
      CALL CLOSE(10)
C***WRITE ADJUSTMENT INFO ON TERMINAL SCREFN
      WRITE(100,2030)
2030  FORMAT(10X,"ANGLES FILTERING COMPLETED ON:")
      WRITE(100,2060) IR(1),ISUB(1),IHOS(1),ITST(1),IPOS(1)
2060  FORMAT(1H,"RECORD NUM:",I3,5X,"SUBJECT NUM:",I3,5X,
1     "HOSP NUM:",I6,5X,"TEST NUM:",I3,5X,"POSITION:",I4)
      WRITE(100,2070) FC1,FC2
2070  FORMAT(10X,"BANDPASS FREQUENCIES:",F9.2," TO",F9.2," HZ")
      KENDR=(KI-1)*4
      WRITE(100,2110) ISBL(2),IOBLK,KENDR,LOT
C***SET PRINTED OUTPUT FLAG
      IY1=IYES !SET TO ALWAYS PRINT
      IF(IY1.NE.IYES) GO TO 100
      WRITE(8,2030)
      WRITE(8,2060) IR(1),ISUB(1),IHOS(1),ITST(1),IPOS(1)
      WRITE(8,2070) FC1,FC2
      WRITE(8,2110) ISBL(2),IOBLK,KENDR,LOT
2110  FORMAT(1H,"FIRST BLOCK:",I4,2X,"LAST BLOCK:",I4,2X,
1     "LAST WORD:",I4,2X,"NUM. OF SAMPLES:",I4)
100  CALL CLOSE(8)
      CALL EXIT
      END

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```

C***      PROGRAM COTRAN
C***      THIS PROGRAM PRODUCES THE DIRECTION COSINE MATRIX:
C***      CT(-,1)          CT(-,2)          CT(-,3)
C***      CT(-,4)          CT(-,5)          CT(-,6)
C***      CT(-,7)          CT(-,8)          CT(-,9)
C***USING THE ANGLES STORED IN SY:NEWANG.DAT. THE MATRIX IS STORED
C*** IN SY:CONTRX.DAT.
C***
C***      TASK BUILD AS: COTRAN=COTRAN,[1,1]F4POTS/LB
C***      UNITS=12          MAXBUF=512
COMMON /ASV/IF16,IF24,IF19
DIMENSION SLATS(6,16),CT(100,10),ANGL(32,4),IPOS(3),IR(3)
DIMENSION ISUB(3),IHOS(3),ITST(3),ISBL(3),IFBL(3),KEND(3)
DIMENSION TSAMP(3),ADJ(3)
DATA IYES/'YE'/,INO/'NO'/
CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
CALL FDBSET(8,'APPEND')
IKB=5
IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
WRITE(100,2000)
2000      FORMAT(20X,'TRANSFORMATION MATRIX COMPUTATION')
IPOST=1          !SET POSITION 1 ONLY
C***ASSIGN AND DEFINE OUTPUT FILE
CALL ASSIGN(9,'SY:CONTRX.DAT;1',16)
DEFINE FILE 9(170,240,U,IF16)
CALL FDBSET(9,'NEW')
C***READ POINTER INDEX FILE
CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
DEFINE FILE 10(1,30,U,IF19)
READ(10'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
IBLK=ISBL(2)          !INPUT BLOCK INDEX
IOBLK=1              !OUTPUT BLOCK INDEX
IF(IPOST.EQ.2) IOBLK=IOBLK+170
IF(IPOST.EQ.3) IOBLK=IOBLK+340
ISBL(3)=IOBLK
KCHK=0              !CYCLE INDEX
KTS1=0              !TEST TO DETECT DISC WRITE
LS=32              !SAMPLES PER INPUT BLOCK
LOT=LS*(IFBL(2)-ISBL(2))+KEND(2)/4
H=TSAMP(3)/1000.0
ITZ=IYES
RADEG=57.29577951
C***ASSIGN AND DEFINE INPUT FILE
CALL ASSIGN(11,'SY:NEWANG.DAT;1',16)
DEFINE FILE 11(65,256,U,IF24)
CALL FDBSET(11,'READONLY')
C***PEAD BLOCK OF INPUT DATA AND INDEX BLOCK AND CYCLE
40      PEAD(11'IBLK) ((ANGL(KI,I),I=1,4),KI=1,LS)
IBLK=IBLK+1
KSTP=KCHK*32
KCHK=KCHK+1
C***CONVERT ANGLES FROM DEGREES TO RADIANS
DO 50 J=1,LS
DO 50 I=1,4
50      ANGL(J,I)=ANGL(J,I)/RADEG
C***COMPUTE AND STORE TRANSFORMATION MATRIX
DO 80 KI=1,LS
KIS=KI+KSTP
C***COMPUTE TRIG FUNCTION VALUES
STH=SIN(ANGL(KI,1))

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      SPH=SIN(ANGL(F1,2))
      SPT=SIN(ANGL(K1,3))
      CTH=SQRT(1.0-STH*STH)
      CPH=SQRT(1.0-SPH*SPH)
      CRT=SQRT(1.0-SBT*SBT)
C***LOAD MATRIX
      CT(KIS,1)=CTH*CRT+STH*SPH*SPT
      CT(KIS,2)=CPH*SBT
      CT(KIS,3)=-STH*CRT+CTH*SPH*SBT
      CT(KIS,4)=-CTH*SBT+STH*SPH*CRT
      CT(KIS,5)=CPH*CRT
      CT(KIS,6)=STH*SPT+CTH*SPH*CRT
      CT(KIS,7)=STH*CPH
      CT(KIS,8)=-SPH
      CT(KIS,9)=CTH*CPH
80      CT(KIS,10)=0.0
C***IF LAST INPUT BLOCK HAS BEEN READ--EXIT LOOP HERE
      IF(IBLK.GT.IFHL(2)) GO TO 140
C***IF 3 CYCLES COMPLETED, SET FOR 8 OUTPUT BLOCKS--EXIT
C*** TO WRITE TO DISC SECTION
      IONUM=8
      IF(KCHK.GE.3) GO TO 360
C***IF ON LAST INPUT BLOCK,REDUCE LS TO LAST WORD
130      IF(IBLK.LT.IFHL(2)) GO TO 40
      LS=(KEND(2)/4)
      GO TO 40
C***OUTPUT TEST SECTION--USED ON LAST INPUT BLOCK ONLY
C***DETERMINE IN WHICH OUTPUT BLOCK LS OCCURS
140      LOS=1+LS+KSTP
      IF(LOS.GT.89) GO TO 290
      IF(LOS.GT.77) GO TO 270
      IF(LOS.GT.65) GO TO 250
      IF(LOS.GT.53) GO TO 230
      IF(LOS.GT.41) GO TO 210
      IF(LOS.GT.29) GO TO 190
      IF(LOS.GT.17) GO TO 170
      IF(LOS.EQ.17) ITZ=INO
      LOSF=16
      IONUM=1
      GO TO 320
170      IF(LOS.EQ.29) ITZ=INO
      LOSF=28
      IONUM=2
      GO TO 320
190      IF(LOS.EQ.41) ITZ=INO
      LOSF=40
      IONUM=3
      GO TO 320
210      IF(LOS.EQ.53) ITZ=INO
      LOSF=52
      IONUM=4
      GO TO 320
230      IF(LOS.EQ.65) ITZ=INO
      LOSF=64
      IONUM=5
      GO TO 320
250      IF(LOS.EQ.77) ITZ=INO
      LOSF=76
      IONUM=6
      GO TO 320
270      IF(LOS.EQ.89) ITZ=INO
      LOSF=88
      IONUM=7
      GO TO 320
290      IF(LOS.EQ.101) ITZ=INO
      LOSF=100

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```

      IONUM=R
C***WRITE ZERO INTO REMAINDER OF LAST OUTPUT BLOCK
320   IF(ITZ.EQ.IND) GO TO 360
      DO 340 KI=LOS,LOSF
      DO 340 I=1,10
340   CT(KI,I)=0.0
      ITZ=IYES
C***WRITE OUTPUT BLOCKS ONTO DISC
360   KIO=1
      DO 380 J=1,IONUM
      KIF=KIO+11
      WRITE(9*IOBLK) ((CT(KI,I),I=1,10),KI=KIO,KIF)
      IOBLK=IOBLK+1
380   KIO=KIO+12
C***RESET CYCLE INDEX AND SET DISC WRITE TEST INDEX
      KTST=1
      KCHF=0
      IF(1BLK.LE.IFBL(2)) GO TO 130
C***CLOSE ALL OPEN FILES
      CALL CLOSE(9)
      CALL CLOSE(11)
C***COMPUTE LAST WORD AND LAST BLOCK WRITTEN TO DISC
      KFND(3)=(LOS-((IONUM-1)*12+5))*10
      IFBL(3)=IOBLK-1
C***WRITE OF TERMINAL SCREEN SCREEN INFORMATION ON COMPUTED MATRIX
      WRITE(100,2030) IR(3),ISUB(3),IHOS(3),ITST(3),IPOST
2030  FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
      1  'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
      WRITE(100,2090) ISBL(2),IFBL(2),KEND(2)
      WRITE(100,2090) ISBL(3),IFBL(3),KEND(3)
      WRITE(100,2060) LOT
2060  FORMAT(1H,5X,'NUMBER OF SAMPLES:',I6)
C***IF DATA LOOKS GOOD--CARRY ON
D     WRITE(100,2050)
2050  FORMAT(10X,'DOES IT LOOK OK? (YES/NO)')
D     READ(1KH,1010) IY
D     IF(IY.NE.IYES) STOP 'MATRIX COMPUTATION ABORTED'
C***WRITE INDEX INFORMATION TO DATA FILE
      CALL ASSIGN(12,'SY:INDACC.DAT;1',16)
      DEFINE FILE 12(1,30,0,IF19)
      CALL FDBSET(12,'OLD')
      WRITE(12*IPOST) IPOS,IR,ISUB,IHOS,ITS1,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(12)
C***SET PRINTED OUTPUT FLAG
      IY1=IYES
      IF(IY1.NE.IYES) GO TO 400
      !SET TO ALWAYS PRINT
      WRITE(8,2070)
2070  FORMAT(1H,19X,'TRANSFORMATION MATRIX COMPUTED FOR')
      WRITE(8,2030) IP(3),ISUB(3),IHOS(3),ITST(3),IPOST
      WRITE(8,2090) ISBL(3),IFBL(3),KEND(3)
2090  FORMAT(1H,'INITIAL BLOCK:',I4,2X,'FINAL BLOCK:',I4,2X,
      1  'LAST WORD:',I4)
400   CALL CLOSE(8)
      CALL EXIT
      END

```

```

C*** PROGRAM COACCL
C*** THIS PROGRAM USES DATA FROM SY:CODATB.DAT AND
C***SY:COMTRX.DAT TO COMPUTE THE INERTIAL ACCELERATION
C***OF THE ACCELEROMETER PLATFORM ORIGIN. THE
C***ACCELERATION ARRAY IS RELATED TO THE INERTIAL AXES BY:
C*** R2DOT(-,1)=ACCELERATION IN THE + X DIRECTION
C*** R2DOT(-,2)=ACCELERATION IN THE + Y DIRECTION
C*** R2DOT(-,3)=ACCELERATION IN THE + Z DIRECTION
C*** R2DOT(-,4)=ZERO
C***THIS ARRAY IS STORED IN DISC FILE SY:ORGACC.DAT.
C***
C*** TASK BUILD AS: COACCL=COACCL,[1,1]F4PLTS/LB
C*** UNITS=12 MAXBUF=512
DIMENSION DATA(96,8),CTIN(96,10),R2DOT(96,4),ASUM(3),IPOS(3)
DIMENSION IR(3),ISUB(3),IHOS(3),ITST(3),ISBL(3),IFBL(3)
DIMENSION KEND(3),TSAMP(3),ADJ(3)
COMMON /ASV/IF17,IF19,IF16,IF21
DATA IYES/'YF'/,INO/'NO'/
CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
CALL FDBSET(8,'APPEND')
IKP=5
IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
WRITE(IOD,2000)
2000 FORMAT(20X,'COMPUTE ORIGIN ACCELERATION')
IPOST=1 !SET POSITION 1 ONLY
C***ASSIGN AND DEFINE INPUT FILES
CALL ASSIGN(9,'SY:CODATB.DAT;1',16)
DEFINE FILE 9(130,256,U,IF17)
CALL FDBSET(9,'READONLY')
CALL ASSIGN(10,'SY:COMTRX.DAT;1',16)
DEFINE FILE 10(170,240,U,IF16)
CALL FDBSET(10,'READONLY')
C***READ INDEX FILE
CALL ASSIGN(11,'SY:INDACC.DAT;1',16)
DEFINE FILE 11(1,30,U,IF19)
CALL FDBSET(11,'READONLY')
READ(11'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
CALL CLOSE(11)
C***SET INPUT INDEXES
KIF=16 !NUMBER OF INPUT SAMPLES PER BLOCK
ILF=8 !NUMBER OF INPUT ARRAY POSITIONS
C***ENTER OFFSETS
DO 10 I=1,3
10 ADJ(I)=0.0
D WRITE(IOD,2010)
2010 FORMAT(10X,'ENTER ACC OFFSETS--1,2,3')
D READ(IKB,1050) (ADJ(I),I=1,3)
1050 FORMAT(3F15.7)
C***OPEN OUTPUT DATA FILE
CALL ASSIGN(12,'SY:ORGACC.DAT;1',16)
DEFINE FILE 12(65,256,U,IF21)
CALL FDBSET(12,'NEW')
C***INITIALIZE INDEXING VARIABLES
IBLK=ISBL(1) !INPUT DATA BLOCK INDEX
IOBLK=ISBL(2) !OUTPUT BLOCK INDEX
IOBLKT=ISBL(3) !ORTHOG TRANS MATRIX BLOCK INDEX
IS=KIF !INPUT DATA SAMPLES PER BLOCK
ISO=12 !ORTHOG TRANS MATRIX SAMPLES PER BLOCK
LOT=IS*(IFBL(1)-ISBL(1))+KEND(1)/ILF
C***READ INPUT DATA AND INDEX BLK NUM
C***READ SUFFICIENT BLOCKS TO FILL 96 SAMPLE ARRAY
INUM=96/KIF

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40      IDNUM=1
      KLR=IBLK
      KIS=1
50      KISF=KIS+LS-1
      READ(9*IBLK) ((DATA(KII,I),I=1,ILF),KII=KIS,KISF)
      IBLK=IBLK+1
      KIS=KIS+LS
C***IF ON LAST BLOCK OF INPUT,REDUCE LS TO LAST WORD
      IF(IBLK.EQ.IFBL(1)) LS=KEND(1)/ILF
C***TEST FOR END OF INPUT DATA
      IF(IBLK.GT.IFBL(1)) GO TO 70
      IDNUM=IDNUM+1
C***TEST IF DATA ARRAY CONTAINS 96 SAMPLES
      IF(IDNUM.GT.INUM) GO TO 70
      GO TO 50
C***READ IN TRANSFORMATION MATRIX AND INDEX BLOCK
70      IINUM=1
      KIST=1
80      KISTF=KIST+LS0-1
      READ(10*IOBLKT) ((CTIN(KI,I),I=1,10),KI=KIS1,KISTF)
      IOBLKT=IOBLKT+1
      KIST=KIST+LS0
C***IF ON LAST BLOCK,REDUCE LS0 TO LAST WORD
      IF(IOBLKT.EQ.IFBL(3)) LS0=KEND(3)/10
C***TEST FOR END OF TRANS MATRIX DATA
      IF(IOBLKT.GT.IFBL(3)) GO TO 100
      ITNUM=ITNUM+1
C***TEST IF MATRIX ARRAY CONTAINS 96 SAMPLES
      IF(ITNUM.GT.8) GO TO 100
      GO TO 80
100     NBLK=IBLK-KLR          !NUM BLOCKS READ THIS LOOP
      NSAM=NBLK*KIF          !NUM SAMPLES THIS LOOP
C***IF WRITING LAST BLOCKS THEN ADJUST NUM SAMPLES
      IF(IBLK.GT.IFBL(1)) NSAM=(NBLK-1)*KIF+LS
C***COMPUTE PLATFORM ORIGIN INERTIAL ACCELERATION
      DO 120 KA=1,NSAM
      ASUM(1)=DATA(KA,5)
      ASUM(2)=(DATA(KA,6)+DATA(KA,7))*0.5
      ASUM(3)=DATA(KA,8)
      R2DOT(KA,1)=CTIN(KA,1)*ASUM(1)+CTIN(KA,2)*ASUM(2)
      1      +CTIN(KA,3)*ASUM(3)-ADJ(1)
      R2DOT(KA,2)=CTIN(KA,4)*ASUM(1)+CTIN(KA,5)*ASUM(2)
      1      +CTIN(KA,6)*ASUM(3)-ADJ(2)
      R2DOT(KA,3)=CTIN(KA,7)*ASUM(1)+CTIN(KA,8)*ASUM(2)
      1      +CTIN(KA,9)*ASUM(3)+1.0-ADJ(3)
120     R2DOT(KA,4)=0.0
C***DETERMINE NUMBER OF OUTPUT BLOCKS AND SET INDEXES
      IF(NSAM.GT.64) GO TO 160
      IF(NSAM.GT.32) GO TO 140
      IF(NSAM.EQ.32) ITZ=INO
      LOSF=32
      IONUM=1
      GO TO 180
140     IF(NSAM.EQ.64) ITZ=INO
      LOSF=64
      IONUM=2
      GO TO 180
160     IF(NSAM.EQ.96) ITZ=INO
      LOSF=96
      IONUM=3
C***IF NECESSARY, WRITE ZERO IN REMAINDER OF LAST OUTPUT BLOCK
180     IF(ITZ.EQ.INO) GO TO 220
      DO 200 KA=NSAM+1,LOSF
      DO 200 I=1,4
200     R2DOT(KA,I)=0.0
C***WRITE OUTPUT TO DISC

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220      KIO=1
        DO 240 J=1,IONUM
          KIFC=KIO+31
          WRITE(12,'IOBLK') ((R2DOT(KI,I),I=1,4),KI=KIO,KIFC)
          IOBLK=IOBLK+1
240      KIO=KIO+32
          ITZ=IYES
          IF(IOBLK.LE.IFBL(1)) GO TO 40
C***CLOSE ALL OPEN FILES
          CALL CLOSE(9)
          CALL CLOSE(10)
          CALL CLOSE(12)
C***COMPUTE WORD POINTER FOR LAST OUTPUT BLOCK
          KENDR=4*(NSAM-(IONUM-1)*32)
          IOBLK=IOBLK-1
C***WRITE ON TERMINAL SCREEN ACCELERATION INFORMATION
          WRITE(100,2140)
          WRITE(100,2070) IR(1),ISUB(1),IHOS(1),ITST(1),IPOST
2070      FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1          'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
          WRITE(100,2080)
2080      FORMAT(7X,'INITIAL BLOCK',2X,'FINAL BLOCK',2X,'FINAL WORD')
          WRITE(100,2090) ISBL(1),IFBL(1),KEND(1)
2090      FORMAT(1H,'DATA',6X,I4,9X,I4,9X,I4)
          WRITE(100,2100) ISBL(2),IOBLK,KENDR
2100      FORMAT(1H,'R2DOT ',4X,I4,9X,I4,9X,I4)
          WRITE(100,2110) TSAMP(1)
2110      FORMAT(2X,'SAMPLE TIME:',F8.1,' (MSECS)')
          WRITE(100,2120) LOT
2120      FORMAT(2X,'NUMBER OF SAMPLES:',I4/)
          WRITE(100,2030) (ADJ(I),I=1,3)
2030      FORMAT(1H,'DATA ADJUSTED USING(1,2,3):',3(2X,G14.7))
C***SET PRINTED OUTPUT FLAG
          IY1=IYES                                !SET TO ALWAYS PRINT
          IF(IY1.NE.IYES) GO TO 300
          WRITE(8,2140)
2140      FORMAT('1',19X,'ORIGIN ACCELERATION COMPUTED FOR')
          WRITE(8,2070) IR(1),ISUB(1),IHOS(1),ITST(1),IPOST
          WRITE(8,2160) ISBL(2),IFBL(2),KEND(2)
2160      FORMAT(1H,'INITIAL BLOCK:',I4,2X,'FINAL BLOCK:',I4,2X,
1          'LAST WORD:',I4)
          WRITE(8,2030) (ADJ(I),I=1,3)
          CALL CLOSE(8)
200      CALL EXIT
          END

```

```

C***      PROGRAM FILACC
C***      THIS PROGRAM FILTERS DATA IN SY:ORGACC.DAT USING AN 8TH ORDER
C***      RECURSIVE BUTTERWORTH FILTER. THE DATA IN SY:ORGACC.DAT IS
C***      REPLACED BY THE FILTERED DATA.
C***
C***      TASK BUILT AS:  FILACC=FILACC,BNDPAS,[1,1]F4POTS/LB
C***      UNITS=10      MAXBUF=512
C***      DIMENSION CODATA(32,4),SIDATA(2000),IPOS(3),IP(3),ISUB(3)
C***      DIMENSION IHOS(3),ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3)
C***      COMMON /ASV/IF22,IF19
C***      DATA IYES/'YE'/
C***      CALL ASSIGN(8,'SY:PRN1IT.LST;1',16)
C***      CALL FDBSET(8,'APPEND')
C***      IKB=5
C***      IOD=5
C***      WRITE PROGRAM TITLE ON TERMINAL SCREEN
C***      WRITE(IOD,2000)
C***      2000      FORMAT(20X,'ORIGIN ACCELERATION FILTERING')
C***      IPOST=1      !SET POSITION 1 ONLY
C***      ASSIGN AND DEFINE INPUT/OUTPUT FILE
C***      CALL ASSIGN(9,'SY:ORGACC.DAT;1',16)
C***      DEFINE FILE 9(65,256,U,IF22)
C***      CALL FDBSET(9,'OLD')
C***      READ POINTER INDEX FILE
C***      CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
C***      DEFINE FILE 10(1,30,U,IF19)
C***      CALL FDBSET(10,'READONLY')
C***      READ(10,IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
C***      CALL CLOSE(10)
C***      ENTER LOWER AND UPPER BANDPASS FREQUENCIES
C***      FC1=0.50      !LOWER SET TO 0.50 HZ
C***      FC2=10.0      !UPPER SET TO 10.0 HZ
C***      SET INITIAL INDEX VALUES
C***      IBLK=ISBL(2)
C***      LS=32
C***      LOT=IS*(IFBL(2)-ISBL(2))+KEND(2)/4
C***      FS=1000.0/TSAMP(2)
C***      II=1
C***      LOAD ALL SAMPLES OF CODATA(=,1) INTO SIDATA
C***      10      READ(9*IBLK) ((CODATA(KI,1),I=1,4),KI=1,LS)
C***      IBLK=IBLK+1
C***      DO 20 KB=1,IS
C***      IND=(IBLK-ISBL(2)-1)*32+KB
C***      SIDATA(IND)=CODATA(KB,II)
C***      IF(IBLK.EQ.IFBL(2)) LS=KEND(2)/4
C***      IF(IBLK.GT.IFBL(2)) GO TO 40
C***      GO TO 10
C***      INCREMENT ARRAY POSITION AND IF LAST POSITION FILTERED EXIT LOOP
C***      30      II=II+1
C***      IF(II.GT.3) GO TO 90
C***      FILTER ONE ARRAY POSITION OF DATA(STORED IN SIDATA)
C***      40      CALL BNDPAS(SIDATA,LOT,FC1,FC2,FS)
C***      RESET BLOCK AND WORD INDEXES
C***      IBLK=ISBL(2)
C***      LS=32
C***      RELOAD CODATA TO REPLACE FILTERED ARRAY POSITION AND TO
C***      LOAD SIDATA WITH NEXT ARRAY POSITION TO BE FILTERED
C***      50      READ(9*IBLK) ((CODATA(KI,1),I=1,4),KI=1,LS)
C***      IORBLK=IBLK
C***      IRLK=IRLK+1
C***      DO 60 KB=1,LS
C***      IND=(IORBLK-ISBL(2))*32+KB
C***      LOAD FILTERED DATA INTO CODATA

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        CODATA(KB,II)=SIDATA(IND)
        IF(II.GE.4) GO TO 60
C***LOAD NEXT ARRAY POSITION TO BE FILTERED INTO SIDATA
        SIDATA(IND)=CODATA(KB,II+1)
60      CONTINUE
C***WRITE FILTERED DATA TO DISC FILE
        WRITE(9'IORLK) ((CODATA(KI,I),I=1,4),KJ=1,LS)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
        IF(IBLK.EQ.IFBL(2)) IS=KEND(2)/4
C***TEST FOR END OF INPUT DATA
        IF(IBLK.GT.IFBL(2)) GO TO 30
        GO TO 50
C***CLOSE OPEN FILE
90      CALL CLOSE(9)
C***WRITE ADJUSTMENT INFO ON TERMINAL SCREEN
        WRITE(10D,2030)
2030     FORMAT(10X,'ORIGIN ACCELERATION FILTERING COMPLETED ON:')
        WRITE(10D,2060) IR(1),ISUR(1),IHOS(1),ITST(1),IPOS(1)
2060     FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1         'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I4)
        WRITE(10D,2070) FC1,FC2
2070     FORMAT(10X,'BANDPASS FREQUENCIES:',F9.2,' TO',F9.2,' HZ')
        KENDR=(KI-1)*4
        WRITE(10D,2110) ISBL(2),IORLK,KENDR,LOT
C***SET PRINTED OUTPUT FLAG
        IY1=IYES                                !SET TO ALWAYS PRINT
        IF(IY1.NE.IYES) GO TO 100
        WRITE(8,2030)
        WRITE(8,2060) IR(1),ISUR(1),IHOS(1),ITST(1),IPOS(1)
        WRITE(8,2070) FC1,FC2
        WRITE(8,2110) ISBL(2),IORLK,KENDR,LOT
2110     FORMAT(1H,'FIRST BLOCK:',I4,2X,'LAST BLOCK:',I4,2X,
1         'LAST WORD:',I4,2X,'NUM. OF SAMPLES:',I4)
100     CALL CLOSE(8)
        CALL EXIT
        END

```

```

C***      PROGRAM ACMEAN
C*** THIS PROGRAM COMPUTES THE MEAN VALUES OF THE ACCELERATIONS
C*** STORED IN SY:ORGACC.DAT. THE COMPUTED MEANS ARE STORED IN ARRAY
C*** SMEAN(2,-) WHICH IS LOADED INTO SY:STMEAN.DAT.
C***
C***      TASK BUILD AS: ACMEAN=ACMEAN,[1,1]F4POTS/LB
C***      UNITS=11      MAXBUF=512
      DIMENSION CODATA(32,8),ASTR(8),IPDS(3),IR(3),ISUB(3),
1  ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3),SMEAN(3,3),IHOS(3)
      COMMON /ASV/IF15,IF19,IF31
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(100,2000)
2000  FORMAT(20X,' ACCELERATION MEAN COMPUTATION')
      IPOST=1      !SET FOR POSITION 1 ONLY
      JSTR=2      !MEANS TO STMEAN(2,-)
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(9,'SY:ORGACC.DAT;1',16)
      DEFINE FILE 9(65,256,U,IF15)
      CALL FDBSET(9,'READONLY')
      IFILE=9
      IPL=2
      IL=4
      KIL=32
C***READ POINTER INDEX FILE
      CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
      DEFINE FILE 10(1,30,U,IF19)
      CALL FDBSET(10,'READONLY')
      READ(10'IPOST) IPDS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(IPL)
      LS=KIL
      LOT=LS*(IFBL(IPL)-ISBL(IPL))+KEND(IPL)/IL
      H=0.01
C***ZERO SUMMING LOCATIONS
      DO 10 I=1,IL
10    ASTR(I)=0.0
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20    READ(IFILE'IBLK) ((CODATA(KI,I),I=1,IL),KI=1,KIL)
      IBLK=IBLK+1
C***COMPUTE SUM OF ALL SAMPLES AND STORE
      DO 30 KI=1,KIL
      DO 30 I=1,IL
30    ASTR(I)=CODATA(KI,I)+ASTR(I)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
      IF(IBLK.EQ.IFBL(IPL)) LS=KEND(IPL)/IL
C***TEST FOR END OF INPUT DATA
      IF(IBLK.GT.IFBL(IPL)) GO TO 40
      GO TO 20
C***CLOSE OPEN FILE
40    CALL CLOSE(IFILE)
C***COMPUTE MEAN VALUE
      DO 50 I=1,IL
50    ASTR(I)=ASTR(I)/FLOAT(LOT)
C***WRITE ADJUSTMENT INFO ON TERMINAL SCREEN
      WRITE(100,2030) (ASTR(I),I=1,IL)
2030  FORMAT(1H,2X,'MEAN(1),(2),.....=',4G15.7,/22X,4G15.7)
C***STORE MEAN DATA IN DISC FILE

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```

CALL ASSIGN(11,'SY:STMEAN.DAT;1',16)
DEFINE FILE 11(1,18,U,IF31)
CALL FDBSET(11,'OLD')
READ(11'IPOST) ((SMEAN(J,I),I=1,3),J=1,3)
DO 55 I=1,3
55  SMEAN(JSTR,I)=ASTR(I)
WRITE(11'IPOST) ((SMEAN(J,I),I=1,3),J=1,3)
CALL CLOSE(11)
C***SET PRINTED OUTPUT FLAG
IY1=IYES !SET TO ALWAYS PRINT
IF(IY1.NE.IYES) GO TO 80
WRITE(8,2330)
2330  FORMAT(15X,'FOR FILE SY:ORGACC.DAT')
70  WRITE(8,2100) IR(IPL),ISUF(IPL),IHOS(IPL),ITST(IPL),IPOST
2100  FORMAT(1H,'RECORD NUM:',I3,5X,'SURJECT NUM:',I3,5X,
1  'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
0  WRITE(8,2110) ISBL(IPL),IFBL(IPL),KEND(IPL),LOT
2110  FORMAT(1H,'FIRST BLOCK:',I4,2X,'LAST BLOCK:',I4,2X,
1  'LAST WORD:',I4,2X,'NUM. OF SAMPLES:',I4)
WRITE(8,2030) (ASTR(I),I=1,IL)
80  CALL CLOSE(8)
CALL EXIT
END

```

```

C***      PROGRAM ADJACC
C*** THIS PROGRAM ADJUSTS THE DATA IN SY:ORGACC.DAT BY SUBTRACTING
C***THE MEAN VALUE STORED IN SY:STMEAN.DAT. THE DATA IN
C***SY:ORGACC.DAT IS REPLACED BY THE ADJUSTED DATA.
C***
C***      TASK BUILD AS: ADJACC=ADJACC,11,11F4POTS/LR
C***      UNITS=12      MAXPUF=512
      DIMENSION CODATA(32,4),SMEAN(3,3)
      DIMENSION IPOS(3),IR(3),ISUB(3),IHOS(3),ITST(3)
      DIMENSION ISBL(3),IFBL(3),KEND(3),TSAMP(3)
      COMMON /ASV/IF19,IF21,IF31
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PFNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(IOD,2000)
2000      FORMAT(20X,'SY:ORGACC.DAT ADJUSTMENT')
      IPOST=1      !SET FOR POSITION 1 ONLY
C***ENTER STORED MEAN ARRAY POSITION TO USE
      JSTR=2      !SMEAN(2,-) FOR ORGACC.DAT
C***READ POINTER INDEX FILE
      CALL ASSIGN(9,'SY:INDACC.DAT;1',16)
      DEFINE FILE 9(1,30,U,IF19)
      CALL FDBSET(9,'READONLY')
      READ(9'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(9)
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(2)      !INPUT BLOCK INDEX
      IOBLK=ISBL(2)      !OUTPUT BLOCK INDEX
      LS=32
      LOT=LS*(IFBL(2)-ISBL(2))+KEND(2)/4
      H=TSAMP(2)/1000.0
C***READ MEANS FROM DISC FILE
      CALL ASSIGN(10,'SY:STMEAN.DAT;1',16)
      DEFINE FILE 10(1,18,U,IF31)
      CALL FDBSET(10,'READONLY')
      READ(10'IPOST) ((SMEAN(J,I),I=1,3),J=1,3)
      CALL CLOSE(10)
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(12,'SY:ORGACC.DAT;1',16)
      DEFINE FILE 12(65,256,U,IF21)
      CALL FDBSET(12,'OLD')
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20      READ(12'IBLK) ((CODATA(KI,I),I=1,4),KI=1,LS)
      IBLK=IBLK+1
C***ADJUST BLOCK OF DATA BY SUBTRACTING MEAN VALUE
      DO 30 KI=1,LS
      DO 30 I=1,3
30      CODATA(KI,I)=CODATA(KI,I)-SMEAN(JSTR,I)
C***WRITE ADJUSTED BLOCK TO DISC FILES AND INDEX BLOCK
50      WRITE(12'IOBLK) ((CODATA(KI,I),I=1,4),KI=1,32)
      IOBLK=IOBLK+1
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
      IF(IOBLK.EQ.IFBL(2)) LS=KEND(2)/4
C***TEST FOR END OF DATA
      IF(IOBLK.GT.IFBL(2)) GO TO 80
      GO TO 20
C***CLOSE ALL OPEN FILES
80      CALL CLOSE(12)
C***COMPUTE LAST WORD AND LAST BLOCK WRITTEN TO DISC
      Lb=LS*4

```

```

      IECLK=IOCLK-1
C***WRITE ON TERMINAL SCREEN MEAN SUBTRACTION INFORMATION
      WRITE(IOD,2070)
      WRITE(IOD,2020) IR(2),ISUR(2),IHOS(2),ITST(2),IPOST
2020  FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
      1  'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
      WRITE(IOD,2090) ISBL(2),IECLK,LW
C***SET PRINTED OUTPUT FLAG
      IY1=IYES                      !SET TO ALWAYS PRINT
      IF(IY1.NE.IYES) GO TO 100
      WRITE(8,2070)
2070  FORMAT(1H,'19X','ORGACC.DAT MEAN ADJUSTMENT COMPLETED ON')
      WRITE(8,2020) IR(2),ISUR(2),IHOS(2),ITST(2),IPOST
D      WRITE(8,2090) ISBL(2),IFBL(2),KEND(2)
2090  FORMAT(1H,'INITIAL BLOCK:',I4,2X,'FINAL BLOCK:',I4,2X,
      1  'LAST WORD:',I4)
100   CALL CLOSE(8)
      CALL EXIT
      END

```



```

C***      PROGRAM CORVEL
C***      THIS PROGRAM INTEGRATES THE ACCELEROMETER DATA STORED
C***      IN SY:ORGACC.DAT TO PRODUCE THE THREE COMPONENTS OF THE
C***      VELOCITY VECTOR. IT STORES COMPONENTS 1=X,2=Y,3=Z AND
C***      MEAN SQ. INTEGRATION ERROR ON DISC FILE SY:ORGVEL.DAT.
C***
C***      TASK BUILD AS: CORVEL=CORVEL,AM3INM,DIRDOT,[1,1]F4POTS/LB
C***      UNITS=11      MAXPUF=512
COMMON Y(37,4),DY(36,4),CODATA(36,4)
DIMENSION IPOS(3),IP(3),ISUB(3),IHOS(3),ITST(3)
DIMENSION ISBL(3),IFBL(3),KEND(3),TSAMP(3)
COMMON /ASV/IF19,IF21,IF22
EXTERNAL DIRDOT
DATA IYES/'YE'/
CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
CALL FDBSET(8,'APPEND')
IKR=5
IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
WRITE(IOD,2000)
2000      FORMAT(20X,'ORIGIN ACCELERATION INTEGRATION')
IPOST=1      !SET FOR POSITION 1 ONLY
C***ASSIGN AND DEFINE OUTPUT FILE
CALL ASSIGN(9,'SY:ORGVEL.DAT;1',16)
DEFINE FILE 9(65,256,U,IF22)
CALL FDBSET(9,'NEW')
C***READ POINTER INDEX FILE
CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
DEFINE FILE 10(1,30,U,IF19)
CALL FDBSET(10,'READONLY')
READ(10'IPOST') IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
IBLK=ISBL(2)      !INPUT BLOCK INDEX
IOBLK=ISBL(2)      !OUTPUT BLOCK INDEX
C***SET INITIAL VALUES FOR ENTRY INTO INTEGRATION ROUTINE AM3INM
C***N.B.: ALL VELOCITY COMPONENTS SET TO ZERO
DO 10 I=1,4
DO 10 J=1,4
Y(J,I)=0.0
10      DY(J,I)=0.0
LS=36      !32 INTEGRATION STEPS PLUS 4 INITIAL VALUES
LOT=(LS-4)*(IFBL(2)-ISBL(2))+KEND(2)/4
H=TSAMP(2)/1000.0
C***ASSIGN AND DEFINE INPUT FILE
CALL ASSIGN(11,'SY:ORGACC.DAT;1',16)
DEFINE FILE 11(65,256,U,IF21)
CALL FDBSET(11,'READONLY')
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20      READ(11'IBLK) ((CODATA(KI,I),I=1,4),KI=5,LS)
IBLK=IBLK+1
C***CONVERT INPUT DATA FROM G'S TO CM/SEC/SEC
DO 40 KI=5,LS
DO 40 I=1,4
40      CODATA(KI,I)=CODATA(KI,I)*981.19
C***INTEGRATE BLOCK OF DATA
C***
CALL AM3INM(DIRDOT,H,LS)
C***
C***IF ON LAST BLOCK,STORE ZERO IN REMAINDER
IF(IOBLK.LT.IFBL(2)) GO TO 50
LOS=LS+1
IF(LOS.GT.36) GO TO 50

```

```

      DO 45 J=L0S,36
      DO 45 I=1,4
      Y(J,I)=0.0
45    DY(J,I)=0.0
C***WRITE INTEGRATED BLOCK TO DISC FILES AND INDEX BLOCK
50    WRITE(9'IOBLK) ((Y(KI,I),I=1,4),KI=5,36)
      IOBLK=IOBLK+1
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD + 4
      IF(IOBLK.EQ.IFBL(2)) LS=(KEND(2)/4)+4
C***TEST FOR END OF DATA
      IF(IOBLK.GT.IFBL(2)) GO TO 80
C***RESET ARRAYS WITH INITIAL CONDITIONS FOR NEXT DATA BLOCK
      DO 60 I=1,4
      DO 60 J=1,4
      Y(J,I)=Y(J+32,I)
      DY(J,I)=DY(J+32,I)
60    CODATA(J,I)=CODATA(J+32,I)
      GO TO 20
C***CLOSE ALL OPEN FILES
80    CALL CLOSE(11)
      CALL CLOSE(9)
C***COMPUTE LAST WORD INTEGRATED AND LAST BLOCK WRITTEN TO DISC
      LW=(LS-4)*4
      IEBLK=IOBLK-1
C***WRITE ON TERMINAL SCREEN INTEGRATION INFORMATION
      WRITE(10D,2070)
      WRITE(10D,2020) IR(2),ISUB(2),IHOS(2),ITST(2),IPOST
2020  FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1    'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
      WRITE(10D,2090) ISBL(2),IEBLK,LW
C***SET PRINTED OUTPUT FLAG
      IY1=IYES                                !SET TO ALWAYS PRINT
      IF(IY1.NE.IYES) GO TO 100
      WRITE(6,2070)
2070  FORMAT(1H,'19X,
1    'ORIGIN ACCELERATION INTEGRATION COMPLETED ON')
      WRITE(6,2020) IP(2),ISUB(2),IHOS(2),ITS1(2),IPOST
      WRITE(6,2090) ISBL(2),IFBL(2),KEND(2)
2090  FORMAT(1H,'INITIAL BLOCK:',I4,2X,'FINAL BLOCK:',I4,2X,
1    'LAST WORD:',I4)
100   CALL CLOSE(8)
      CALL EXIT
      END

```

```

      SUPROUTINE DIRDOT(IY,LDY)
C*** THIS SUBROUTINE CONTAINS THE DIFFERENTIAL EQUATIONS
C***WHICH DEFINE THE SOLUTION TO BOTH THE ACCELEROMETER
C***PLATFORM ORIGIN VELOCITY AND POSITION.
      COMMON Y(37,4),DY(36,4),CODATA(36,4)
      DY(LDY,1)=CODATA(LDY,1)
      DY(LDY,2)=CODATA(LDY,2)
      DY(LDY,3)=CODATA(LDY,3)
      RETURN
      END

```

```

C***      PROGRAM FILVEL
C***      THIS PROGRAM FILTERS DATA IN SY:ORGVEL.DAT USING AN 8TH ORDER
C***RECURSIVE BUTTERWORTH FILTER. THE DATA IN SY:ORGVEL.DAT IS
C***REPLACED BY THE FILTERED DATA.
C***
C***      TASK BUILD AS:  FILVEL=FILVEL,BNDPAS,[1,1]F4POTS/LB
C***      UNITS=10      MAXBUF=512
      DIMENSION CODATA(32,4),SIDATA(2000),IPOS(3),IR(3),ISUB(3)
      DIMENSION IHOS(3),ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3)
      COMMON /ASV/IF22,IF19
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKP=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(IOD,2000)
2000      FORMAT(20X,'OPIGIN VELOCITY FILTERING')
      IPOST=1      !SET FOR POSITION 1 ONLY
C***ASSIGN AND DEFINE INPUT/OUTPUT FILE
      CALL ASSIGN(9,'SY:ORGVEL.DAT;1',16)
      DEFINE FILE 9(65,256,U,IF22)
      CALL FDBSET(9,'OLD')
C***READ POINTER INDEX FILE
      CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
      DEFINE FILE 10(1,30,U,IF19)
      CALL FDBSET(10,'READONLY')
      READ(10'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(10)
C***ENTER LOWER AND UPPER BANDPASS FREQUENCIES
      FC1=0.50      !LOWER SET TO 0.50 HZ
      FC2=10.0      !UPPER SET TO 10.0 HZ
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(2)
      LS=32
      LOT=LS*(IFBL(2)-ISBL(2))+KEND(2)/4
      FS=1000.0/TSAMP(2)
      II=1
C***LOAD ALL SAMPLES OF CODATA(-,1) INTO SIDATA
10      READ(9'IBLK) ((CODATA(KI,I),I=1,4),KI=1,LS)
      IBLK=IBLK+1
      DO 20 KB=1,LS
      IND=(IBLK-ISBL(2)-1)*32+KB
20      SIDATA(IND)=CODATA(KB,II)
      IF(IBLK.EQ.IFBL(2)) LS=KEND(2)/4
      IF(IBLK.GT.IFBL(2)) GO TO 40
      GO TO 10
C***INCREMENT ARRAY POSITION AND IF LAST POSITION FILTERED EXIT LOOP
30      II=II+1
      IF(II.GT.3) GO TO 90
C***FILTER ONE ARRAY POSITION OF DATA(STORED IN SIDATA)
40      CALL BNDPAS(SIDATA,LOT,FC1,FC2,FS)
C***RESET BLOCK AND WORD INDEXES
      IBLK=ISBL(2)
      LS=32
C***RELOAD CODATA TO REPLACE FILTERED ARRAY POSITION AND TO
C***LOAD SIDATA WITH NEXT ARRAY POSITION TO BE FILTERED
50      READ(9'IBLK) ((CODATA(KI,I),I=1,4),KI=1,LS)
      IOBLK=IBLK
      IBLK=IBLK+1
      DO 60 KB=1,LS
      IND=(IOBLK-ISBL(2))*32+KB
C***LOAD FILTERED DATA INTO CODATA

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```

        CODATA(KB,II)=SIDATA(IND)
        IF(II.GE.4) GO TO 60
C***LOAD NEXT ARRAY POSITION TO BE FILTERED INTO SIDATA
        SIDATA(IND)=CODATA(KB,II+1)
60      CONTINUE
C***WRITE FILTERED DATA TO DISC FILE
        WRITE(9'IOBLK) ((CODATA(KI,I),I=1,4),KI=1,LS)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
        IF(IBLK.EQ.IFBL(2)) LS=KEND(2)/4
C***TEST FOR END OF INPUT DATA
        IF(IPLK.GT.IFBL(2)) GO TO 30
        GO TO 50
C***CLOSE OPEN FILE
90      CALL CLOSE(9)
C***WRITE ADJUSTMENT INFO ON TERMINAL SCREEN
        WRITE(10D,2030)
2030     FORMAT(10X,'ORIGIN VELOCITY FILTERING COMPLETED ON:')
        WRITE(10D,2060) IR(1),ISUB(1),IHOS(1),ITST(1),IPOS(1)
2060     FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1         'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I4)
        WRITE(10D,2070) FC1,FC2
2070     FORMAT(10X,'BANDPASS FREQUENCIES:',F9.2,' TO',F9.2,' HZ')
        KENDR=(KI-1)*4
        WRITE(10D,2110) ISBL(2),IOBLK,KENDR,LOT
C***SET PRINTED OUTPUT FLAG
        IY1=IYES                                !SET TO ALWAYS PRINT
        IF(IY1.NE.IYES) GO TO 100
        WRITE(8,2030)
        WRITE(8,2060) IR(1),ISUB(1),IHOS(1),ITST(1),IPOS(1)
        WRITE(8,2070) FC1,FC2
        WRITE(8,2110) ISBL(2),IOBLK,KENDR,LOT
2110     FORMAT(1H,'FIRST BLOCK:',I4,2X,'LAST BLOCK:',I4,2X,
1         'LAST WORD:',I4,2X,'NUM. OF SAMPLES:',I4)
100     CALL CLOSE(8)
        CALL EXIT
        END

```

```

C***      PROGRAM VEMEAN
C*** THIS PROGRAM COMPUTES THE MEAN VALUES OF THE VELOCITIES
C***STORED IN SY:ORGVFL.DAT. THE COMPUTED MEANS ARE STORED IN ARRAY
C***SMEAN(3,-) WHICH IS LOADED INTO SY:STMEAN.DAT.
C***
C***      TASK BUILD AS: VEMEAN=VEMEAN,(1,1)F4POTS/LB
C***                      UNITS=11          MAXBUF=512
      DIMENSION CODATA(32,8),ASTR(8),IPOS(3),IR(3),ISUR(3),
1      ITST(3),ISBL(3),IFBL(3),KEND(3),TSAMP(3),SMEAN(3,3),IHOS(3)
      COMMON /ASV/IF15,IF19,IF31
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKH=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(100,2000)
2000      FORMAT(20X,' VELOCITY MEAN COMPUTATION')
      IPOST=1          !SET FOR POSITION 1 ONLY
      JSTR=3          !MEANS TO STMEAN(3,-)
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(9,'SY:ORGVFL.DAT;1',16)
      DEFINE FILE 9(65,256,U,IF15)
      CALL FDBSET(9,'READONLY')
      IFILE=9
      IPL=2
      IL=1
      KIL=32
C***READ POINTER INDEX FILE
      CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
      DEFINE FILE 10(1,30,U,IF19)
      CALL FDBSET(10,'READONLY')
      READ(10'IPOST) IPOS,IR,ISUR,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
      IRL=ISBL(IPL)
      LS=KIL
      LOT=LS*(IFBL(IPL)-ISBL(IPL))+KEND(IPL)/IL
      H=0.01
C***ZERO SUMMING LOCATIONS
      DO 10 I=1,IL
10      ASTR(I)=0.0
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20      READ(IFILE'IBLK) ((CODATA(KI,I),J=1,IL),KI=1,KIL)
      IBLK=IBLK+1
C***COMPUTE SUM OF ALL SAMPLES AND STORE
      DO 30 KI=1,KIL
      DO 30 I=1,IL
30      ASTR(I)=CODATA(KI,I)+ASTR(I)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
      IF(IBLK.EQ.IFBL(IPL)) LS=KEND(IPL)/IL
C***TEST FOR END OF INPUT DATA
      IF(IRLK.GT.IFBL(IPL)) GO TO 40
      GO TO 20
C***CLOSE OPEN FILE
40      CALL CLOSE(IFILE)
C***COMPUTE MEAN VALUE
      DO 50 J=1,IL
50      ASTR(I)=ASTR(J)/FLOAT(LOT)
C***WRITE ADJUSTMENT INFO ON TERMINAL SCREEN
      WRITE(100,2030) (ASTR(I),I=1,IL)
2030      FORMAT(1H,2X,'MEAN(1),(2),.....=',4G15.7,/22X,4G15.7)
C***STORE MEAN DATA IN DISC FILE

```

```

CALL ASSIGN(11,'SY:SIMFAN.DAT;1',16)
DEFINE FILE 11(1,18,0,IF31)
CALL FDBSET(11,'OLD')
READ(11'IPOST) ((SMEAN(J,I),I=1,3),J=1,3)
DO 55 I=1,3
55  SMEAN(JSTR,I)=ASTR(I)
WRITE(11'IPOST) ((SMEAN(J,I),I=1,3),J=1,3)
CALL CLOSE(11)
C***SET PRINTED OUTPUT FLAG
IY1=IYES ISET TO ALWAYS PRINT
IF(IY1.NE.IYES) GO TO 80
WRITE(8,2330)
2330  FORMAT(15X,'FOR FILE SY:ORGVEL.DAT')
70  WRITE(8,2100) IR(IPL),ISUB(IPL),IHOS(IPL),ITST(IPL),IPOST
2100  FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1  'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
D  WRITE(8,2110) ISBL(IPL),IFBL(IPL),KEND(IPL),LOT
2110  FORMAT(1H,'FIRST BLOCK:',I4,2X,'LAST BLOCK:',I4,2X,
1  'LAST WORD:',I4,2X,'NUM. OF SAMPLES:',I4)
WRITE(8,2030) (ASTR(I),I=1,IL)
80  CALL CLOSE(8)
CALL EXIT
END

```

```

C***      PROGRAM ADJVEL
C*** THIS PROGRAM ADJUSTS THE DATA IN SY:ORGVFL.DAT BY SUBTRACTING
C***THE MEAN VALUE STORED IN SY:STMEAN.DAT. THE DATA IN
C***SY:ORGVFL.DAT IS REPLACED BY THE ADJUSTED DATA.
C***
C***      TASK BUILD AS: ADJVEL=ADJVEL,[1,1]F4POTS/LB
C***      UNITS=12      MAXBUF=512
      DIMENSION CODATA(32,4),SMEAN(3,3)
      DIMENSION IPOS(3),IP(3),ISUB(3),IHOS(3),ITST(3)
      DIMENSION ISBL(3),IFBL(3),KEND(3),TSAMP(3)
      COMMON /ASV/IF19,IF21,IF31
      DATA IYES/'YE'/
      CALL ASSIGN(8,'SY:PRNTIT.LST;1',16)
      CALL FDBSET(8,'APPEND')
      IKB=5
      IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
      WRITE(IOD,2000)
2000      FORMAT(20X,'SY:ORGVFL.DAT ADJUSTMENT')
      IPOST=1      !SET FOR POSITION 1 ONLY
C***ENTER STORED MEAN ARRAY POSITION TO USE
      JSTR=3      !SMEAN(3,-) FOR ORGVFL.DAT
C***READ POINTER INDEX FILE
      CALL ASSIGN(9,'SY:INDACC.DAT;1',16)
      DEFINE FILE 9(1,30,U,IF19)
      CALL FDBSET(9,'READONLY')
      READ(9'IPOST) IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
      CALL CLOSE(9)
C***SET INITIAL INDEX VALUES
      IBLK=ISBL(2)      !INPUT BLOCK INDEX
      IOBLK=ISBL(2)      !OUTPUT BLOCK INDEX
      LS=32
      LDT=LS*(IFBL(2)-ISBL(2))+KEND(2)/4
      H=TSAMP(2)/1000.0
C***READ MEANS FROM DISC FILE
      CALL ASSIGN(10,'SY:STMEAN.DAT;1',16)
      DEFINE FILE 10(1,18,U,IF31)
      CALL FDBSET(10,'READONLY')
      READ(10'IPOST) ((SMEAN(J,I),I=1,3),J=1,3)
      CALL CLOSE(10)
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(12,'SY:ORGVFL.DAT;1',16)
      DEFINE FILE 12(65,256,U,IF21)
      CALL FDBSET(12,'OLD')
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20      READ(12'IBLK) ((CODATA(KI,I),I=1,4),KI=1,LS)
      IBLK=IBLK+1
C***ADJUST BLOCK OF DATA BY SUBTRACTING MEAN VALUE
      DO 30 KI=1,LS
      DO 30 I=1,3
30      CODATA(KI,I)=CODATA(KI,I)-SMEAN(JSTR,I)
C***WRITE ADJUSTED BLOCK TO DISC FILES AND INDEX BLOCK
50      WRITE(12'IOBLK) ((CODATA(KI,I),I=1,4),KI=1,32)
      IOBLK=IOBLK+1
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
      IF(IOBLK.EQ.IFBL(2)) LS=KEND(2)/4
C***TEST FOR END OF DATA
      IF(IOBLK.GT.IFBL(2)) GO TO 80
      GO TO 20
C***CLOSE ALL OPEN FILES
80      CALL CLOSE(12)
C***COMPUTE LAST WORD AND LAST BLOCK WRITTEN TO DISC
      LW=LS*4

```

```

      IECLK=IOCLK-1
C***WRITE ON TERMINAL SCREEN MEAN SUBTRACTION INFORMATION
      WRITE(IOD,2070)
      WRITE(IOD,2020) IR(2),ISUB(2),IHOS(2),ITST(2),IPOST
2020  FORMAT(1H , 'RECORD NUM:',I3,5X, 'SUBJECT NUM:',I3,5X,
      1  'HOSP NUM:',J6,5X, 'TEST NUM:',I3,5X, 'POSITION:',I3)
      WRITE(IOD,2090) ISBL(2),IECLK,LW
C***SET PRINTED OUTPUT FLAG
      IY1=IYFS                                !SET TO ALWAYS PRINT
      IF(IY1.NE.IYES) GO TO 100
      WRITE(8,2070)
2070  FORMAT(1H ,19X, 'ONGVEL.DAT MEAN ADJUSTMENT COMPLETED ON')
      WRITE(8,2020) IR(2),ISUB(2),IHOS(2),ITST(2),IPOST
D      WRITE(8,2090) ISBL(2),IFBL(2),KEND(2)
2090  FORMAT(1H , 'INITIAL BLOCK:',I4,2X, 'FINAL BLOCK:',I4,2X,
      1  'LAST WORD:',I4)
100   CALL CLOSE(8)
      CALL EXIT
      END

```



```

C***  PROGRAM CORPOS
C***  THIS PROGRAM INTEGRATES THE VELOCITY DATA STORED
C***IN SY:ORGVEL.DAT TO PRODUCE THE THREE COMPONENTS OF THE
C***POSITION VECTOR. IT STORES COMPONENTS 1=X,2=Y,3=Z AND
C***MEAN SO. INTEGRATION ERROR ON DISC FILE SY:ORGPPOS.DAT.
C***
C***  TASK BUILD AS:  CORPOS=CORPOS,AM3INM,DIRDOT,[1,1]F4POTS/LB
C***                   UNITS=11          MAXRUF=512
COMMON Y(37,4),DY(36,4),CODATA(36,4)
DIMENSION IPOS(3),IR(3),ISUB(3),IHOS(3),ITST(3)
DIMENSION ISBL(3),IFBL(3),KEND(3),TSAMP(3)
COMMON /ASV/IF19,IF22,IF23
EXTERNAL DIRDOT
DATA IYES/'YE'/
CALL ASSIGN(8,'SY:PENTIT.LST;1',16)
CALL FDBSET(8,'APPEND')
IKB=5
IOD=5
C***WRITE PROGRAM TITLE ON TERMINAL SCREEN
WRITE(IOD,2000)
2000  FORMAT(20X,'ORIGIN VELOCITY INTEGRATION')
      IPOST=1          !SET FOR POSITION 1 ONLY
C***ASSIGN AND DEFINE INPUT FILE
CALL ASSIGN(9,'SY:ORGVEL.DAT;1',16)
DEFINE FILE 9(65,256,U,IF22)
CALL FDBSET(9,'READONLY')
C***READ POINTER INDEX FILE
CALL ASSIGN(10,'SY:INDACC.DAT;1',16)
DEFINE FILE 10(1,30,U,IF19)
CALL FDBSET(10,'READONLY')
READ(10'IPOST') IPOS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
IBLK=ISBL(2)          !INPUT BLOCK INDEX
IOBLK=ISBL(2)         !OUTPUT BLOCK INDEX
C***SET INITIAL VALUES FOR ENTRY INTO INTEGRATION ROUTINE AM3INM
C***N.B.:ALL VELOCITY COMPONENTS SET TO ZERO
DO 10 I=1,4
DO 10 J=1,4
Y(J,I)=0.0
10  DY(J,I)=0.0
      LS=36          !32 INTEGRATION STEPS PLUS 4 INITIAL VALUES
      LOT=(LS-4)*(IFBL(2)-ISBL(2))+KEND(2)/4
      H=TSAMP(2)/1000.0
C***ASSIGN AND DEFINE OUTPUT FILE
CALL ASSIGN(11,'SY:ORGPPOS.DAT;1',16)
DEFINE FILE 11(65,256,U,IF23)
CALL FDBSET(11,'NEW')
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20  READ(9'IBLK') ((CODATA(KI,I),I=1,4),KI=5,LS)
      IBLK=IBLK+1
C***INTEGRATE BLOCK OF DATA
C***
      CALL AM3INM(DIRDOT,H,LS)
C***
C***IF ON LAST BLOCK,STORE ZERO IN REMAINDER
      IF(IOBLK.LT.IFBL(2)) GO TO 50
      LOS=LS+1
      IF(LOS.GT.36) GO TO 50
      DO 45 J=LOS,36
      DO 45 I=1,4
      Y(J,I)=0.0
45  DY(J,I)=0.0

```

```

C***WRITE INTEGRATED BLOCK TO DISC FILES AND INDEX BLOCK
50   WRITE(11,'IOBLK') ((Y(KI,I),I=1,4),KI=5,36)
      IOBLK=IOBLK+1
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD + 4
      IF(IOBLK.EQ.IFRL(2)) LS=(KEND(2)/4)+4
C***TEST FOR END OF DATA
      IF(IOBLK.GT.IFRL(2)) GO TO 80
C***RESET ARRAYS WITH INITIAL CONDITIONS FOR NEXT DATA BLOCK
      DO 60 I=1,4
      DO 60 J=1,4
      Y(J,I)=Y(J+32,I)
      DY(J,I)=DY(J+32,I)
60   CODATA(J,I)=CODATA(J+32,I)
      GO TO 20
C***CLOSE ALL OPEN FILES
90   CALL CLOSE(9)
      CALL CLOSE(11)
C***COMPUTE LAST WORD INTEGRATED AND LAST BLOCK WRITTEN TO DISC
      LW=(LS-4)*4
      IECLK=IOBLK-1
C***WRITE ON TERMINAL SCREEN INTEGRATION INFORMATION
      WRITE(10D,2070)
      WRITE(10D,2020) IR(2),ISUB(2),IHOS(2),ITST(2),IPOST
2020  FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
1     'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3)
      WRITE(10D,2090) ISBL(2),IECLK,LW
C***SET PRINTED OUTPUT FLAG
      IY1=IYES                                !SET TO ALWAYS PRINT
      IF(IY1.NE.IYES) GO TO 100
      WRITE(8,2070)
2070  FORMAT(1H,19X,'ORIGIN VELOCITY INTEGRATION COMPLETED ON')
      WRITE(8,2020) IR(2),ISUB(2),IHOS(2),ITST(2),IPOST
      WRITE(8,2090) ISBL(2),IFRL(2),KEND(2)
2090  FORMAT(1H,'INITIAL BLOCK:',I4,2X,'FINAL BLOCK:',I4,2X,
1     'LAST WORD:',I4)
100   CALL CLOSE(8)
      CALL EXIT
      END

```

Program DATRUN

This is a command file program
which automatically executes all
the programs listed below.
Execute by @DATRUN

RUN DATCON
RUN STADAT
RUN FILDAT
RUN SWPDAT
RUN SPEDIT
RUN DMGFIL
RUN INACHG
RUN COANGL
RUN FILANG
RUN COTRAG
RUN COACCL
RUN FILACC
RUN ACMEAN
RUN ADJACC
RUN CORVEL
RUN FILVEL
RUN VFMEAN
RUN ADJVEL
RUN CORPOS

```

C***  PROGRAM PLOTIB
C***  THIS PROGRAM PLOTS UP TO 4 CHANNELS(OR ARRAY POSITIONS) OF
C***DATA STORED IN DISC DATA FILES LISTED IN THE INPUT FILE
C***SECTION OF THE PROGRAM. A MAXIMUM OF 1024 SAMPLES CAN BE
C***PLOTTED(UP TO 10.12 SECS). THE PLOT SIZE IS 18CM X 24CM.
C***WHEN PSIZ IS SET TO 1.5, THE PLOT IS FULL SIZED FOR TX AND
C*** PLOTTER.
C***
C***      LINK AS  PLOTIP=PLOTIB,PLOTL,SYSLIB/F
C***
COMMON /ASV/IF17,IF15,IF16,IF30,IF21,IF22,IF23,IF24,IF25
DIMENSION LABEL(16)
DIMENSION DATBLK(32,10),DATA(512,4),YDATA(512),TIME(512)
LOGICAL*1 CODE(6)
DATA IYES/'YE'/
DATA LABEL/'1','2','3','4','5','6','7','8','9','10',
1  '11','12','13','14','15','16'/
DATA ICODAT/'CO'/,IOMEG/'OM'/,IORPOS/'PO'/,IRBAKT/'RB'/
DATA ITRANS/'TR'/,IORTHO/'OR'/,IACCL/'R2'/,IORVEL/'VE'/
DATA IANGL/'AN'/
IKB=5
IOD=7
C***ENTER NAME SYMBOL OF DISC FILE TO BE PLOTTED
WRITE(IOD,2000)
2000  FORMAT(20X,'PLOT PROGRAM'/10X,'ENTER FILE NAME '
1  /10X,'(CO=CODATM,OM=OMEGA,TR=TRANSM,OR=TRORTH)'
2  /10X,'(R2=GRACCL,VE=ORGVEL,PO=ORGPOS,RB=FLATEN,AN=ANGLES)')
READ(IKB,1000) INAM
1000  FORMAT(A2)
WRITE(IOD,2010)
2010  FORMAT(10X,'ENTER FILE STARTING BLK NUM')
READ(IKB,1010) ITBLK
1010  FORMAT(I4)
C***BRANCH TO SELECTED DISC FILE
IF(INAM.EQ.ICODAT) GO TO 30
IF(INAM.EQ.IOMEG) GO TO 40
IF(INAM.EQ.ITRANS) GO TO 60
IF(INAM.EQ.IORTHO) GO TO 70
IF(INAM.EQ.IACCL) GO TO 80
IF(INAM.EQ.IORVEL) GO TO 90
IF(INAM.EQ.IORPOS) GO TO 100
IF(INAM.EQ.IRBAKT) GO TO 110
IF(INAM.EQ.IANGL) GO TO 120
C***ASSIGN AND DEFINE SELECTED FILE AND SET INDEXES
30  CALL ASSIGN(17,'DK0:CODATA.DAT',14,'OLD')
    DEFINE FILE 17(260,256,U,IF17)
    IFILE=17
    IMAX=32          !MAX NUMBER OF BLOCKS
    KIF=16           !NUMBER OF SAMPLES PER BLOCK
    ILF=8            !NUMBER OF ARRAY POSITIONS IN DISC FILE
    TBLK=0.16        !SECONDS PER BLOCK
    GO TO 140
40  CALL ASSIGN(15,'DK0:OMEGA.DAT',13,'OLD')
    DEFINE FILE 15(130,256,U,IF15)
    IFILE=15
50  IMAX=16
    KIF=32
    ILF=4
    TBLK=0.32
    GO TO 140
60  CALL ASSIGN(30,'DK0:TRANSA.DAT',14,'OLD')
    DEFINE FILE 30(180,240,U,IF30)

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65      IMAX=42
      KIF=12
      ILF=10
      TBLK=0,12
      GO TO 140
70      CALL ASSIGN(16,'DK0:TRORTA.DAT',14,'OLD')
      DEFINE FILE 16(340,240,U,IF16)
      IFILE=16
      GO TO 65
80      CALL ASSIGN(21,'DK0:ORACCB.DAT',14,'OLD')
      DEFINE FILE 21(130,256,U,IF21)
      IFILE=21
      GO TO 50
90      CALL ASSIGN(22,'DK0:ORGVER.DAT',14,'OLD')
      DEFINE FILE 22(130,256,U,IF22)
      IFILE=22
      GO TO 50
100     CALL ASSIGN(23,'DK0:ORGPOR.DAT',14,'OLD')
      DEFINE FILE 23(130,256,U,IF23)
      IFILE=23
      GO TO 50
110     CALL ASSIGN(25,'DK0:FLATEN.DAT',14,'OLD')
      DEFINE FILE 25(130,256,U,IF25)
      IFILE=25
      GO TO 50
120     CALL ASSIGN(24,'DK0:ANGLES.DAT',14,'OLD')
      DEFINE FILE 24(130,256,U,IF24)
      IFILE=24
      GO TO 50
C***ENTER PLOT START AND FINISH BLOCK NUMBERS AND TEST
140     WRITE(100,2040) IMAX
2040    FORMAT(10X,'ENTER PLOT START AND FINISH BLK NUM: '/15X,
1      'MAX=',12,2X,'IF EVERY POINT PLOTTED')
      READ(100,1020) ISBLK,IFBLK
1020    FORMAT(2I4)
      IF(((IFBLK-ISBLK)+1).GT.IMAX*4) STOP 'BLOCK LIMIT EXCEEDED'
      KSTP=1 ! INDEX TO LOAD EVERY POINT OF DATA
      IF(((IFBLK-ISBLK)+1).GT.IMAX) KSTP=2 !LOAD ALTERNATE PTS
      IF(((IFBLK-ISBLK)+1).GT.IMAX*2) KSTP=4 !LOAD EVERY 4TH PT
C***ENTER NUMBER OF CHANNELS(OR ARRAY POSITIONS)TO BE PLOTTED;TEST
      WRITE(100,2060)
2060    FORMAT(10X,'ENTER FIRST AND LAST PLOT ARRAY NUMBER:MAX=4'
1      '/10X,'**LAST MUST BE .GE. FIRST**')
      READ(100,1020) ISPL,IFPL
      IF(((IFPL-ISPL)+1).GT.4) IFPL=ISPL+3 !INSURE MAX 4 PLOTS
      IF(ISPL.GT.IFPL) STOP 'FIRST ARRAY PLOT NUM .GT. LAST'
C***ENTER PLOT AND TEXT SCALING FACTORS
      PSIZ=1.5
      TSIZ=1.0
C***SET INITIAL VALUES
      WRITE(100,2080)
2080    FORMAT(5X,'ENTER CODE(1-2-2-1 DIGITS):DISC,REC,SUB,TEST')
      READ(100,1040) CODE
1040    FORMAT(6A1)
C      WRITE(100,2070)
2070    FORMAT(10X,'ENTER STEP SIZE(100HZ-0.01,200HZ-0.005)')
C      READ(100,1030) H
1030    FORMAT(F15.7)
      H=0.005 !SET STEP SIZE FOR 200 HZ ONLY
      IBLK=ISBLK
      IPTS=((IFBLK-ISBLK)+1)*KIF/KSTP
      IF(IPTS.GT.512) STOP 'IPTS COMPUTED .GT. 512'
C***BEGIN LOOP TO LOAD DISC DATA INTO DATA ARRAY
160     READ(IFILE=IBLK) ((DATBLK(KI,IL),IL=1,ILF),KI=1,KIF)
      DO 180 KB=1,KIF,KSTP
      IND=(IPLK-ISBLK)*KIF/KSTP+KB/KSTP+KSTP/2

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        IF(KSTP.EQ.4) IND=IND-1
        DO 170 KC=ISPL,IFPL
170      DATA(IND,KC-ISPL+1)=DATBLK(KK,KC)
180      TIME(IND)=FLOAT((IBLK-ITBLK)*KIF+(KE-1))*H
        IF(IBLK.EQ.IFBLK) GO TO 200
        IBLK=IBLK+1
        GO TO 160
C***CLOSE OPEN DISC FILE
200      CALL CLOSE(IFILE)
C***BEGIN PLOTTING ROUTINE
        CALL PLOTST
        CALL FACTOR(Psiz)
        CALL TEXTS(Tsiz)
C***SET THE REQUIRED INTERVAL NUMBERS AND SIZE FOR THE Y-AXIS
        IP=IFPL-ISPL+1          !NUMBER OF PLOTS (1 TO 4)
        RIP=FLOAT(IP)
        S=12.0/RIP              !Y-AXIS SIZE IN CMS
C***MOVE ORIGIN TO BOTTOM LEFT OF PLOT
        XOR=20.0                !20 MM FROM LEFT EDGE
        YOR=20.0                !20 MM FROM BOTTOM
        CALL PLOT(XOR,YOR,-3)
C***SCALE AND DRAW X-AXIS (22 CM LONG)
        BKPCM=FLOAT((IFBLK-ISBLK)+2) !NUM OF BLOCKS + 1
        IF(H.LT.0.008) TBLK=TBLK*0.5 !BLOCK TIME @200HZ
        IDX=IFIX(BKPCM/22.0*TBLK*100.0) !FIX(SEC/CM*100.)
        DX=FLOAT(IDX)/100.0          !CONVERT TO 2 DIGITS
        IF(DX.LT.1.0E-4) DX=TBLK*0.05
        XMIN=TIME(1)
        CALL AXIS(0.0,0.0,'TIME (SECS)',11,22.0,0.0,XMIN,DX)
C***MOVE ORIGIN TO TOP LEFT OF FIRST PLOT
        YOR=(12.0+RIP-0.5)*10.0
        CALL PLOT(0.0,YOR,-3)
C***WRITE CODE NUMBER
        TSIZ=0.8
        CALL SYMBOL(20.,-6.,6.,CODE,0.0,6)
        TSIZ=1.0
        CALL PLOT(0.0,0.0,3)
C***WRITE TITLE OF DATA BEING PLOTTED
C***  MOVE PEN TO TITLE STARTING POINT
        XTO=100.0
        YTO=-7.0
        SNAMSZ=6.0
        IF(INAM.EQ.ICODAT) GO TO 310
        IF(INAM.EQ.IOMEG) GO TO 320
        IF(INAM.EQ.ITRANS) GO TO 340
        IF(INAM.EQ.IORTHO) GO TO 350
        IF(INAM.EQ.IACCL) GO TO 360
        IF(INAM.EQ.IORVEL) GO TO 370
        IF(INAM.EQ.IORPOS) GO TO 380
        IF(INAM.EQ.IRBAKT) GO TO 390
        IF(INAM.EQ.IANGL) GO TO 500
310      CALL SYMBOL(XTO,YTO,SNAMSZ,'CODATA',0.0,6)
        GO TO 400
320      CALL SYMBOL(XTO,YTO,SNAMSZ,'OMEGA',0.0,5)
        GO TO 400
340      CALL SYMBOL(XTO,YTO,SNAMSZ,'TRANS MATRIX',0.0,12)
        GO TO 400
350      CALL SYMBOL(XTO,YTO,SNAMSZ,'ORTHO MATRIX',0.0,12)
        GO TO 400
360      CALL SYMBOL(XTO,YTO,SNAMSZ,'ORGACCL',0.0,7)
        GO TO 400
370      CALL SYMBOL(XTO,YTO,SNAMSZ,'ORGVEL',0.0,6)
        GO TO 400
380      CALL SYMBOL(XTO,YTO,SNAMSZ,'ORGPOS',0.0,6)
        GO TO 400
390      CALL SYMBOL(XTO,YTO,SNAMSZ,'IRBAKT',0.0,6)
        GO TO 400
500      CALL SYMBOL(XTO,YTO,SNAMSZ,'ANGLE',0.0,6)

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      GO TO 400
500    CALL SYMBOL(XTO,YTO,SNAMSZ,'ANGLES THET,PHI,BET',0.0,19)
C***BEGIN THE PLOTTING LOOP
400    DO 450 I=ISPL,IFPL
C***LOAD THE YDATA ARRAY
      DO 410 II=1,IPTS
10     YDATA(II)=DATA(II,I-ISPL+1)
C***MOVE THE ORIGIN TO BOTTOM LEFT OF CURRENT PLOT
      YOR=-(S+1.0)*10.0
      IF(I.EQ.ISPL) YOR=-S*10.0
      CALL PLOT(0.0,YOR,-3)
C***SCALE AND DRAW THE Y-AXIS (S CM HIGH)
      CALL SCALE(YDATA,S,IPTS,1,YMIN,DY)
      CALL AXIS(0.0,0.0,LABEL(I),-2,S,90.0,YMIN,DY)
C***MOVE THE PEN TO Y = ZERO POSITION AND DRAW Y=0 LINE
      YZER=-YMIN/DY*10.0
      XZREND=(TIME(IPTS)-XMIN)/DX*10.0
      CALL PLOT(0.0,YZER,3)
      CALL PLOT(XZREND,YZER,2)
      CALL PLOT(0.0,YZER,3)
C***PLOT THIS LINE
      DO 430 II=1,IPTS
      XX=(TIME(II)-XMIN)/DX*10.0
      YY=(YDATA(II)-YMIN)/DY*10.0
430    CALL PLOT(XX,YY,2)
450    CONTINUE
      CALL PLOTND
      CALL EXIT
      END

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C***      PROGRAM SCNPOS
C***      THIS PROGRAM LOCATES THE CENTRAL 3 STRIDES IN THE WALK BY FINDING
C***      THE MINIMUM POSITIONS IN THE VERTICAL DIRECTION .
C***
C***      TASK BUILD AS: SCNPOS=SCNPOS,[1,1]F4POTS/LB
C***      UNITS=11      MAXBUF=512
      DIMENSION CUDATA(32,4),ASTR(3),IPOS(3),IR(3),ISUB(3),IHOS(3)
      DIMENSION ITST(3),ISHL(3),IFBL(3),KEND(3),TSAMP(3)
      DIMENSION ACCMXY(50),IMNBLK(50),IMNIND(50),TIMMXX(50),TIMMAX(6,3)
      DIMENSION INWHLK(7),INWIND(7),TIMNEW(7),ACCMAX(6,3),ACCMIN(6,3)
      DIMENSION TIMMIN(6,3),SUMPEK(3),PEAK(6,3),SUMMAX(3),SUMPIN(3)
      DIMENSION SIGMAX(3),SIGMIN(3),SIGPEK(3),ITITLE(9,5),IALPHA(8,6)
      DIMENSION INDNAM(6),IFLNAM(8),ILOCN(7)
      LOGICAL*1 IDATE(9),ITIME(8)
      COMMON /ASV/IF15,IF19,IF31
      DATA IALPHA(1,1),IALPHA(2,1),IALPHA(3,1),IALPHA(4,1),IALPHA(5,1),
1      IALPHA(6,1),IALPHA(7,1)/"SY",":O","RG","AC","C","DA","T;"/
      DATA IALPHA(1,2),IALPHA(2,2),IALPHA(3,2),IALPHA(4,2),IALPHA(5,2),
1      IALPHA(6,2),IALPHA(7,2)/"SY",":O","RG","VE","L","DA","T;"/
      DATA IALPHA(1,3),IALPHA(2,3),IALPHA(3,3),IALPHA(4,3),IALPHA(5,3),
1      IALPHA(6,3),IALPHA(7,3)/"SY",":O","RG","PO","S","DA","T;"/
      DATA IALPHA(1,4),IALPHA(2,4),IALPHA(3,4),IALPHA(4,4),IALPHA(5,4),
1      IALPHA(6,4),IALPHA(7,4)/"SY",":","OM","EG","A","DA","T;"/
      DATA IALPHA(1,5),IALPHA(2,5),IALPHA(3,5),IALPHA(4,5),IALPHA(5,5),
1      IALPHA(6,5),IALPHA(7,5)/"SY",":N","E","AN","G","DA","T;"/
      DATA IALPHA(1,6),IALPHA(2,6),IALPHA(3,6),IALPHA(4,6),IALPHA(5,6),
1      IALPHA(6,6),IALPHA(7,6)/"SY",":I","ND","AC","C","DA","T;"/
      DATA ITITLE(1,1),ITITLE(2,1),ITITLE(3,1),ITITLE(4,1),ITITLE(5,1),
1      ITITLE(6,1),ITITLE(7,1),ITITLE(8,1),ITITLE(9,1)/"AC","CE",
2      "LE","PA","TI","ON",":","",""/
      DATA ITITLE(1,2),ITITLE(2,2),ITITLE(3,2),ITITLE(4,2),ITITLE(5,2),
1      ITITLE(6,2),ITITLE(7,2),ITITLE(8,2),ITITLE(9,2)/"VE","LO",
2      "CI","TY",":","",""/
      DATA ITITLE(1,3),ITITLE(2,3),ITITLE(3,3),ITITLE(4,3),ITITLE(5,3),
1      ITITLE(6,3),ITITLE(7,3),ITITLE(8,3),ITITLE(9,3)/"PO","SI",
2      "TI","ON",":","",""/
      DATA ITITLE(1,4),ITITLE(2,4),ITITLE(3,4),ITITLE(4,4),ITITLE(5,4),
1      ITITLE(6,4),ITITLE(7,4),ITITLE(8,4),ITITLE(9,4)/"AN","GU",
2      "LA","R","VE","LO","CI","TY",":",""/
      DATA ITITLE(1,5),ITITLE(2,5),ITITLE(3,5),ITITLE(4,5),ITITLE(5,5),
1      ITITLE(6,5),ITITLE(7,5),ITITLE(8,5),ITITLE(9,5)/"AN","GL",
2      "FS",":","",""/
      DATA IYES/"YE"/,INO/"NO"/
      CALL ASSIGN(8,"SY:DUMPRN.LST;1",15)
      CALL FDBSET(8,"NEW")
      IKR=5
      IOD=5
C***WRITE PROGRAM TITLE ON TFRMIAL SCREEN
      WRITE(100,2000)
2000      FORMAT(20X,"CFNTRAL 3 STRIDES LOCATOR")
      IPOST=1      !SET FOR POSITION 1 ONLY
C***ENTER VERSION NUMBER OF DATA FILES
      WRITE(100,2300)
2300      FORMAT(2X,"ENTER VERISON NUMBER OF DATA RECORDS")
      READ(IKB,1300) IALPHA(8,1)
1300      FORMAT(A2)
1010      FORMAT(I6)
C***LOAD OTHER DATA FILE NAMES WITH VERSION NUMBER
      DO 5 I=2,6
5      IALPHA(8,I)=IALPHA(8,1)
      WRITE(100,2310) (IALPHA(K,3),K=1,8)
2310      FORMAT(2X,"FILES:",2X,8A2)

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DO 6 K=1,8
6   INDNAM(K)=IALPHA(K,6)
   CALL ASSIGN(10,INDNAM,16)
   DEFINE FILE 10(1,30,U,IF19)
   CALL FDBSET(10,"READONLY")
   RFAD(10"IPGST) IPGS,IR,ISUB,IHOS,ITST,ISBL,IFBL,KEND,TSAMP
   CALL CLOSE(10)
C***SET INITIAL INDEX VALUES
   IFLAG=-10                      !MEAN COMPUTATION FLAG
   DO 7 I=1,7
   INWBLK(I)=0
7   INWIND(I)=0
   IPL=2
   IL=4
   KIL=32
   IBLK=ISBL(IPL)
   LS=KIL
   LOT=LS*(IFBL(IPL)-ISBL(IPL))+KEND(IPL)/IL
   H=0.005
C***BEGIN TO SEARCH POSITION DATA FILE
   IIFF=3
C***ASSIGN AND DEFINE INPUT FILE
   DO 8 KK=1,8
8   IFLNAM(KK)=IALPHA(KK,IIFF)
   CALL ASSIGN(9,IFLNAM,16)
   DEFINE FILE 9(65,256,U,IF15)
   CALL FDBSET(9,"READONLY")
   IFILE=9
C***ZERO SUMMING LOCATIONS
   DO 10 I=1,3
10  ASTR(I)=0.0
   IF(IFLAG.LT.0) GO TO 20
   IBLK=INWBLK(1)
   IFBL(IPL)=INWBLK(7)
   KEND(IPL)=IL*INWIND(7)
   LOT=KIL*(IFBL(IPL)-IBLK)+(INWIND(1)-KIL+INWIND(7))/IL
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
20  READ(IFILE"IBLK) ((CODATA(KI,I),I=1,IL),KI=1,KIL)
   KIA=1
   LS=KIL
   IF(IBLK.EQ.INWBLK(1)) KIA=INWIND(1)
   IBLK=IBLK+1
C***COMPUTE SUM OF ALL SAMPLES AND STORE
   DO 30 KI=KIA,LS
   DO 30 I=1,3
30  AST(I)=CODATA(KI,I)+AST(I)
C***IF ON LAST BLOCK,REDUCE LS TO LAST WORD
   IF(IBLK.EQ.IFBL(IPL)) LS=KEND(IPL)/IL
C***TEST FOR END OF INPUT DATA
   IF(IBLK.GT.IFBL(IPL)) GO TO 40
   GO TO 20
C***COMPUTE MEAN VALUE
40  DO 50 J=1,3
50  ASTR(I)=AST(I)/FLOAT(LOT)
C***SET INDEXES FOR FINDING ALL POS(3) MINIMUMS
   ILOC=0                      !MINIMUM LOCATION INDEX
   ILOOP=-1 !INSURES 1ST MIN INDEX IS 1 IF START NEGATIVE
   IBLK=ISBL(IPL) !RESET TO FIRST BLOCK OF DATA
C***SET ALL MINIMUM PARAMETERS TO INITIAL VALUES
   DO 60 J=1,50
   ACCMXX(I)=10000.
   IMNBLK(I)=0
   IMNIND(I)=0
60  TIMMXX(I)=0.0
C***READ BLOCK OF INPUT DATA AND INDEX BLOCK
70  READ(IFILE"IBLK) ((CODATA(KI,I),I=1,IL),KI=1,KIL)

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      IFIK=JBLK+1
C***SUBTRACT MEAN VALUE AND SEARCH FOR MINIMUMS
      DO 90 KB=1,FIL
      CODATA(KB,3)=CODATA(KB,3)-ASTR(3)
      IF(CODATA(KB,3).GT.0.0) GO TO 80
C***MINIMUM SEARCH LOOP
      IF(JLOOP.LT.0) ILOC=ILOC+1
      ILOOP=+1
      IF(CODATA(KB,3).GT.ACCMXX(ILOC)) GO TO 90
      ACCMXX(ILOC)=CODATA(KB,3)
      IMNBLK(ILOC)=IBLK-1
      IMNIND(ILOC)=KB
      TIMMXX(ILOC)=FLOAT((IFLK-1-ISRL(IPL))*KIL+(KB-1))*H
      GO TO 90
C***MAXIMUM SEARCH LOOP
      80      JLOOP=-1
      90      CONTINUE
C***TEST FOR END OF INPUT DATA
      IF(IBLK.GT.IFBL(IPL)) GO TO 100
      GO TO 70
C***RESTORE MINIMUM TO CORRECT ABSOLUTE VALUE
      100     DO 110 I=1,ILOC
      110     ACCMXX(I)=ACCMXX(I)+ASTR(3)
C***WRITE DATA ON TERMINAL SCREEN
      WRITE(100,2010)
      2010    FORMAT(2X,'ILOC',2X,'BLK',2X,'IND',2X,'TIME',2X,'ACCMXX')
      DO 120 I=1,ILOC
      120     WRITE(100,2020) I,IMNBLK(I),IMNIND(I),TIMMXX(I),ACCMXX(I)
      2020    FORMAT(2X,I3,3X,I3,3X,I2,2X,F4.2,2X,G10.3)
C***CLOSE OPEN FILE
      CALL CLOSE(IFILE)
C***SET PRINTED OUTPUT FLAG
      IY1=INO          !SET TO NOT PRINT
      IF(IY1.NE.IYES) GO TO 400
C***ONLY PRINT HEADER INFORMATION ONE TIME
      IF(IIFF.NE.1) GO TO 300
      CALL DATE(IDATE)
      CALL TIME(ETIME)
      WRITE(8,2095) IDATE,ETIME
      2095    FORMAT(15X,'STATISTICS FOR CENTRAL 3 STRIDES',15X,9A1,2X,
      1        'AT ',8A1)
      WRITE(8,2100) IR(IPL),ISUB(IPL),IHOS(IPL),ITST(IPL),IPOST,
      1        CAD
      2100    FORMAT(1H,'RECORD NUM:',I3,5X,'SUBJECT NUM:',I3,5X,
      1        'HOSP NUM:',I6,5X,'TEST NUM:',I3,5X,'POSITION:',I3,
      2        5X,'CADENCE =',F7.2,' STEPS/MINUTE')
      WRITE(8,2120)
      2120    FORMAT(5X,'STEP SECTION POINTS',5X,'1',6X,'2',6X,'3',6X,'4',
      1        6X,'5',6X,'6',6X,'7')
      WRITE(8,2130) (INWBLK(I),I=1,7)
      2130    FORMAT(20X,'BLOCK:',2X,I2,6(5X,I2))
      WRITE(8,2140) (INWIND(I),I=1,7)
      2140    FORMAT(20X,'WORD:',2X,I2,6(5X,I2))
      WRITE(8,2160) (TIMNEW(I),I=1,7)
      2160    FORMAT(20X,'TIME:',7(F7.2))
      300     WRITE(8,2190) (ITITLE(JJ,IIFF),JJ=1,9)
      2190    FORMAT(6X,9A2)
      DO 380 I=1,3
      WRITE(8,2200) I
      WRITE(8,2210) (ACCMAX(K,I),K=1,6),SUMMAX(I),SIGMAX(I)
      WRITE(8,2220) (TIMMAX(K,I),K=1,6)
      WRITE(8,2230) (ACCMIN(K,I),K=1,6),SUMMIN(I),SIGMIN(I)
      WRITE(8,2240) (TIMMIN(K,I),K=1,6)
      380     WRITE(8,2260) (PEAK(K,I),K=1,6),SUMPEK(I),SIGPEK(I)
      2200    FORMAT(5X,'AXIS',I2,15X,'1-2',8X,'2-3',8X,'3-4',8X,'4-5',8X,
      1        '5-6',8X,'6-7',8X,'MEAN',7X,'SIGMA')

```

```
2210  FORMAT(10X,"MAX VALUES: ",8(G11.4))
2220  FORMAT(10X,"MAX TIMES: ",6(G11.4))
2230  FORMAT(10X,"MIN VALUES: ",8(G11.4))
2240  FORMAT(10X,"MIN TIMES: ",6(G11.4))
2260  FORMAT(10X,"PK TO PK: ",8(G11.4))
      WRITE(8,5000)
      !ADDED DUE TO LP MALFUNCT
5000  FORMAT(2X,/)
400   CALL CLOSE(8)
      CALL EXIT
```

```

C***  PROGRAM STORE3
C***  THIS PROGRAM CONDENSES THE 3 WALKING CYCLES INTO
C***THE SAME NUMBER OF POINTS FOR ALL 7 SUBJECTS. IT
C***THEN STORES THE DATA IN FILES
C*** SY:$SSV@.DAT;* WHERE $$$=ACC,POS,VEL,UMG,ANG ;
C*** R=1,2,3 AND #=VERSION NUMBER. ONLY ONE ARRAY
C***POSITION IS STORED IN EACH DATA FILE.
C***
C***          TASK BUILD AS: STORE3=STORE3,[1,1]F4POTS/LB
C***          UNITS=11          MAXBUF=512
C***
      DIMENSION CODATA(32,4),DATA(600),IPDS(3),IR(3),ISUB(3),
1          IHOS(3),ITST(3),ISBL(3),IFBL(3),KEND(3),
2          TSAMP(3),INDX(200),IFLNAM(8)
      LOGICAL*1 IDATE(9),ITIME(8)
      DATA IYES/'YE'/
      IKB=5
      IOD=5
C*** WRITE PROGRAM NAME ON TERMINAL SCREEN
      WRITE(IOD,2000)
2000  FORMAT(2X,'3 CYCLE CONDENSING PROGRAM')
      IPOST=1
C***ENTER INPUT DATA FILE NAME
20  WRITE(IOD,2010)
2010  FORMAT(2X,'ENTER FILENAME -FILNAM.DAT;**)
      READ(IFB,1000) (IFLNAM(I),I=1,8)
1000  FORMAT(8A2)
      WRITE(IOD,1000) (IFLNAM(I),I=1,8)
C***ENTER ARRAY POSITION TO BE STORED
      WRITE(IOD,2012)
2012  FORMAT(2X,'ENTER ARRAY POSITION TO STORE')
      READ(IKB,1020) III
C***ENTER STARTING AND FINISHING BLOCK AND WORD AND THE NUMBER
C*** OF POINTS TO BE KEPT IN CONDENSED DATA FILE
      WRITE(IOD,2020)
2020  FORMAT(2X,'ENTER: FIRST BLK,FIRST WRD, LAST BLK, LAST WRD',
1          /,10X,'AND NUM POINTS FOR COND FILE')
      READ(IKB,1010) ISBLK,ISWRD,IFBLK,IFWRD,IDPTS
1010  FORMAT(5I6)
      WRITE(IOD,2030) ISBLK,ISWRD,IFBLK,IFWRD
2030  FORMAT(2X,'FIRST BLK,WRD:',2I4,' LAST BLK,WRD:',2I4)
1020  FORMAT(14)
C***COMPUTE DROP POINTS AND INDX(1)
      NDPTS=(IFBLK-ISBLK-1)*32+33+IFWRD-ISWRD
      IDROP=NDPTS-IDPTS
      INDX(1)=IDPTS/IDROP/2
      WRITE(IOD,2050) IDPTS,NDPTS,IDROP,INDX(1)
2050  FORMAT(2X,'IDPTS=',I3,' NDPTS=',I3,' IDROP=',I3,
1          ' INDX(1)=',I3)
C***ASSIGN AND DEFINE INPUT FILE
      CALL ASSIGN(9,IFLNAM,16)
      DEFINE FILE 9(65,256,U,1F9)
      CALL FDBSET(9,'READONLY')
      IFILE=9
C***SET INITIAL INDEXES
      KIL=32
      IL=4
      IND=1
      KF=1
      DRPTS=FLGAT(IDROP)
      DTPTS=FLGAT(IDPTS)
      IBLK=ISBLK
C***READ BLOCK OF INPUT DATA

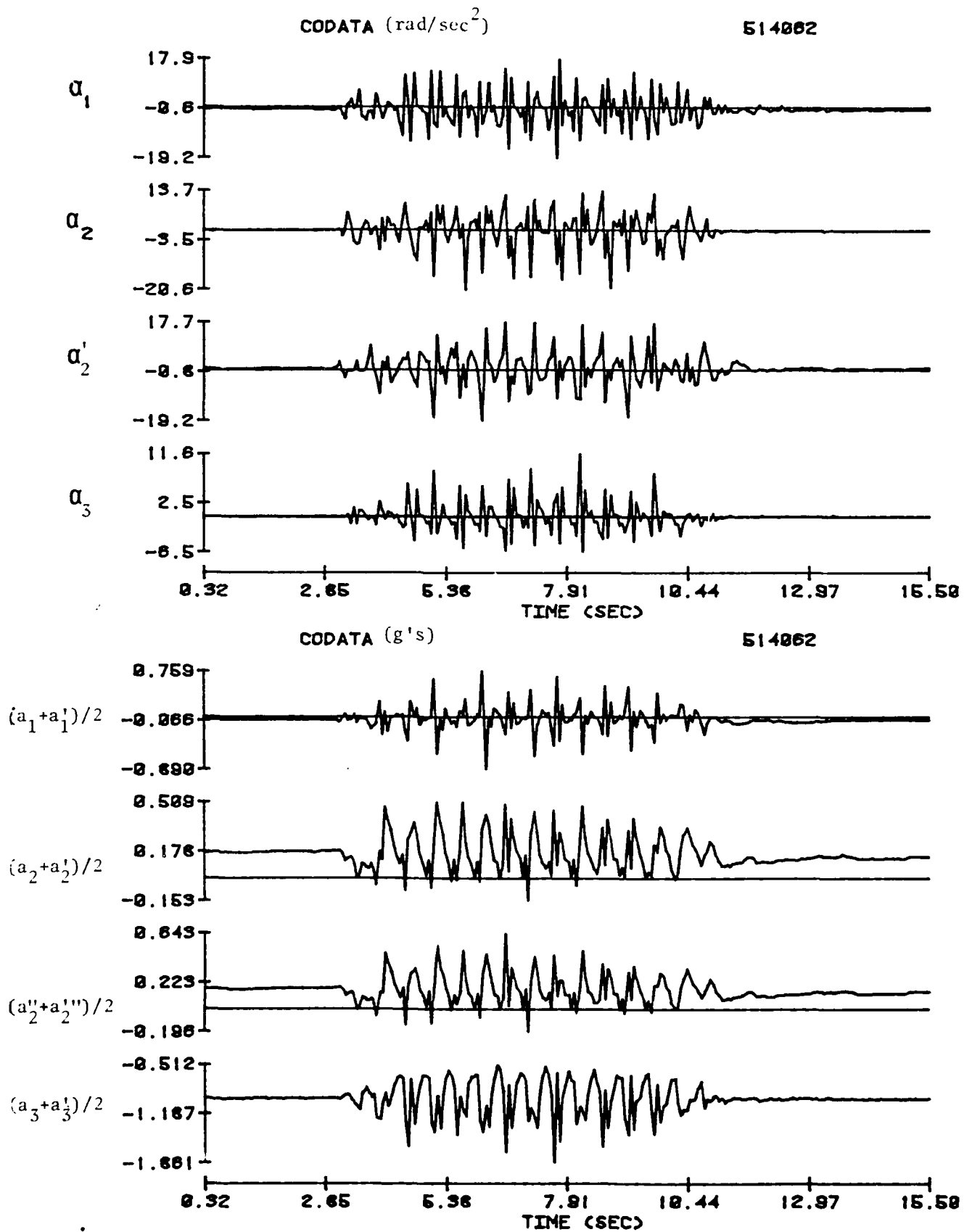
```

```

50      READ(IFILE,IBLK) ((CODATA(KI,I),I=1,IL),KI=1,KIL)
      KRS=1          !STARTING WORD INDEX
      KRF=32         !FINISHING WORD INDEX
      IF(IBLK.EQ.ISBLK) KRS=ISWRD
      IF(IBLK.EQ.IFBLK) KRF=IFWRD
C***TESTING ONLY, WRITE OUT INDEXES TO CHECK
D      WRITE(IOD,3000) IND,IBLK,KRS,KRF
3000    FORMAT(2X,"IND:",I4," IBLK:",I3," KRS:",I3," KRF:",I3)
C***LOAD DATA INTO DATA ARRAY
      DO 70 KH=KRS,KRF
      IF(INDX(KP).NE.IND) GO TO 60
      KP=KP+1
3010    FORMAT(2X,"INDX(KP)",I3," KP:",I3," IND:",I3)
      DK=FLOAT(KP)
      INDX(KP)=INDX(1)+IFIX((DTPTS/DRPTS)*(DK-1.0))
C***TESTING ONLY WRITE OUT INDX(KP),KP AND IND
D      WRITE(IOD,3010) INDX(KP),KP,IND
      GO TO 70
60      DATA(IND)=CODATA(KB,III)
      IND=IND+1
70      CONTINUE
C***INDEX BLOCK AND CHECK IF ALL DATA READ IN
      IBLK=IBLK+1
      IF(IBLK.LE.IFBLK) GO TO 50
C***CLOSE OPEN FILE
      CALL CLOSE(IFILE)
C***WRITE OUT NUM OF PTS LOADED,NUM PTS DROPPED,NUM PTS SAVED
      WRITE(IOD,2060) IND-1,KP-1,IDPTS
2060    FORMAT(2X,"PTS LDED:",I3," PTS DROPED:",I3," IDPTS:",I3)
C***WRITE OUT INDEX OF POINTS DROPPED
      WRITE(IOD,2065) (INDX(J),J=1,KP-1)
2065    FORMAT(20(2X,I0I4,/))
C***ENTER OUTPUT FILE NAME
      WRITE(IOD,2070)
2070    FORMAT(2X,"ENTER OUTPUT FILENAME ~FILNAM.DAT;***")
      READ(IKB,1000) (IFLNAM(I),I=1,8)
      WRITE(IOD,1000) (IFLNAM(I),I=1,8)
C***WRITE CONDENSED DATA TO DISC
      CALL ASSIGN(10,IFLNAM,16)
      WRITE(10) IDPTS,(DATA(I),I=1,IDPTS)
      CALL CLOSE(10)
C***LOOP BACK TO START IF DESIRED
      WRITE(IOD,2080)
2080    FORMAT(2X,"DO YOU WANT TO STOP?(YES/NO)")
      READ(IKB,1030) IY1
1030    FORMAT(A2)
      IF(IY1.NE.IYES) GO TO 20
100     CALL EXIT
      END

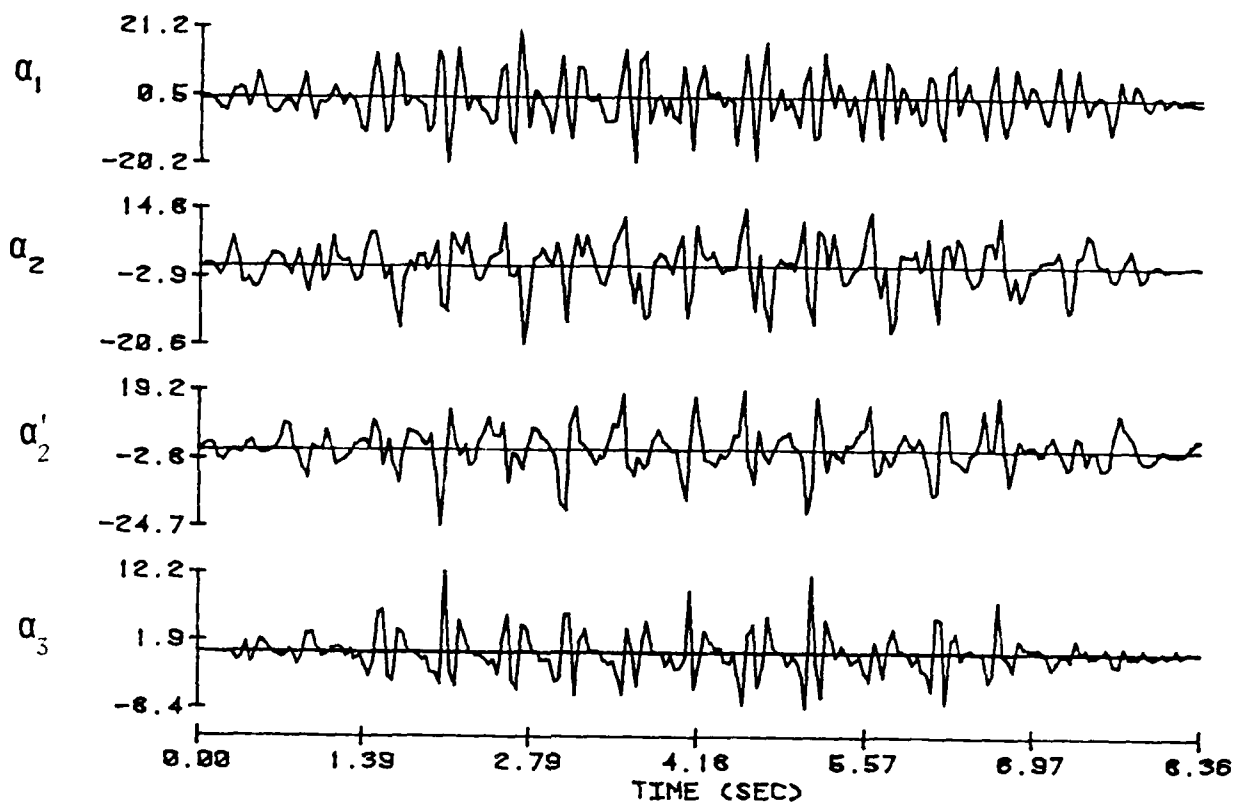
```

Typical Plots from Data Processing



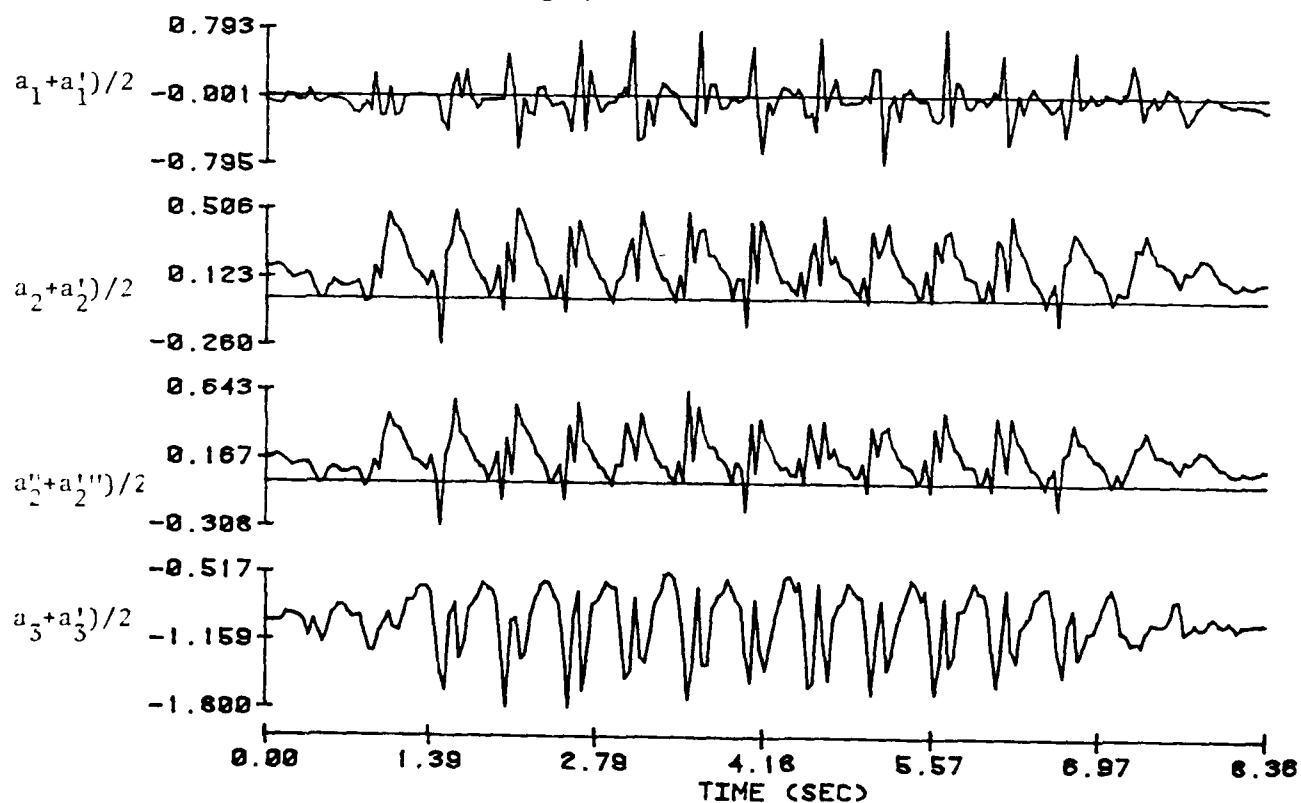
CODATB (rad/sec²)

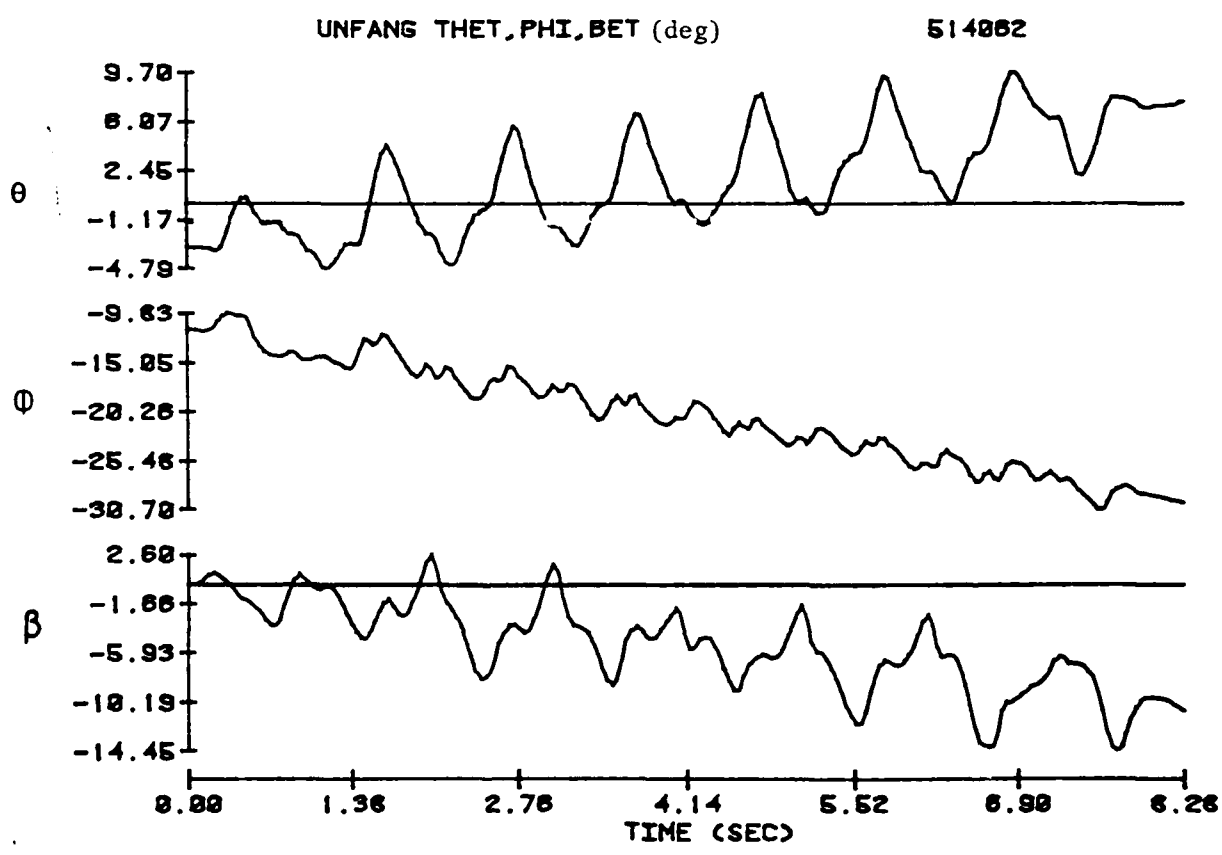
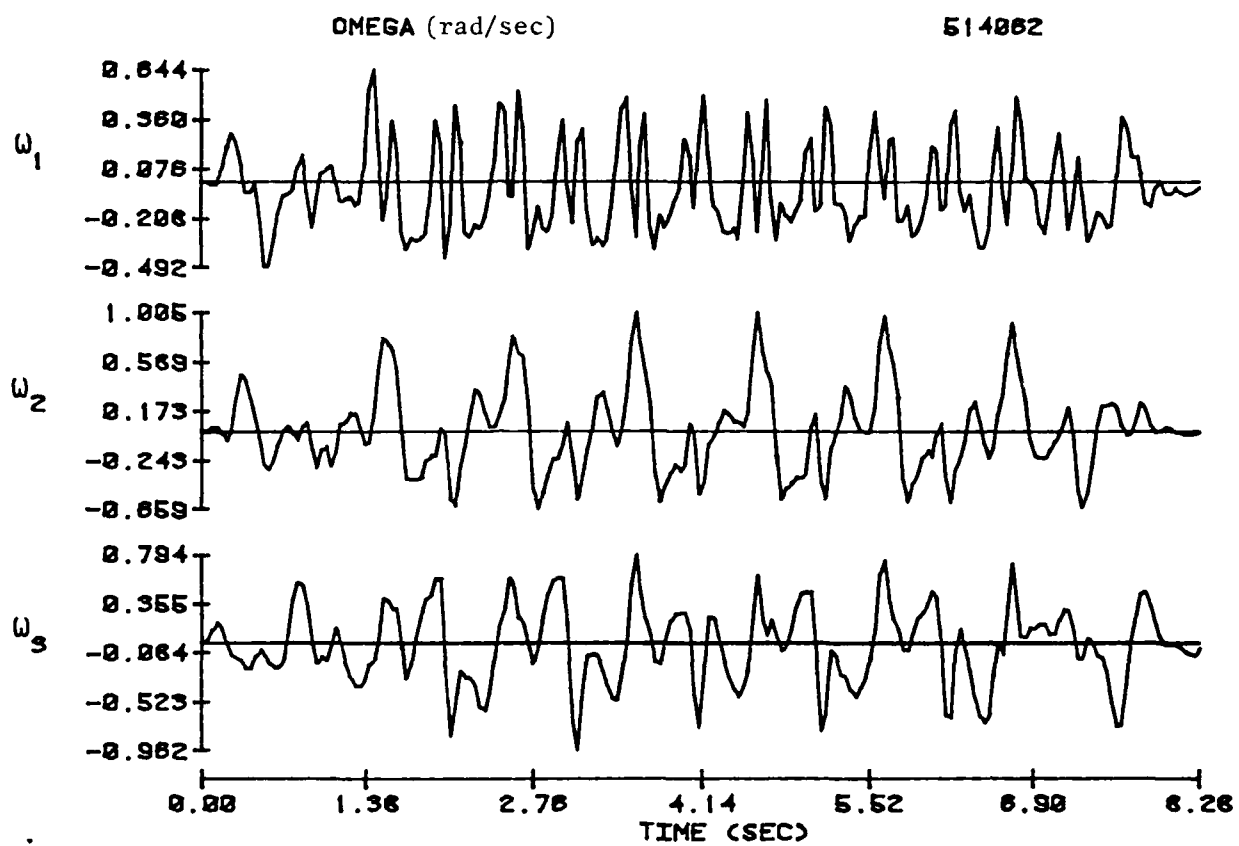
514862



CODATB (g's)

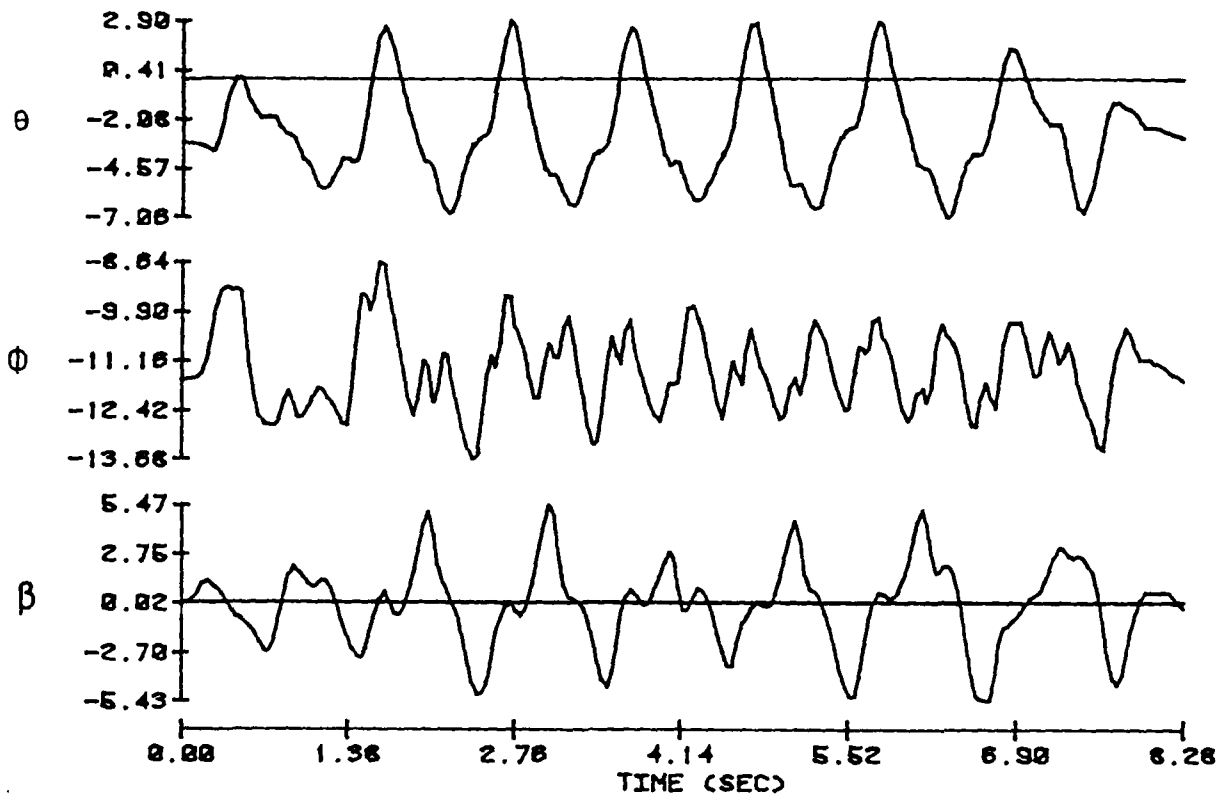
514862





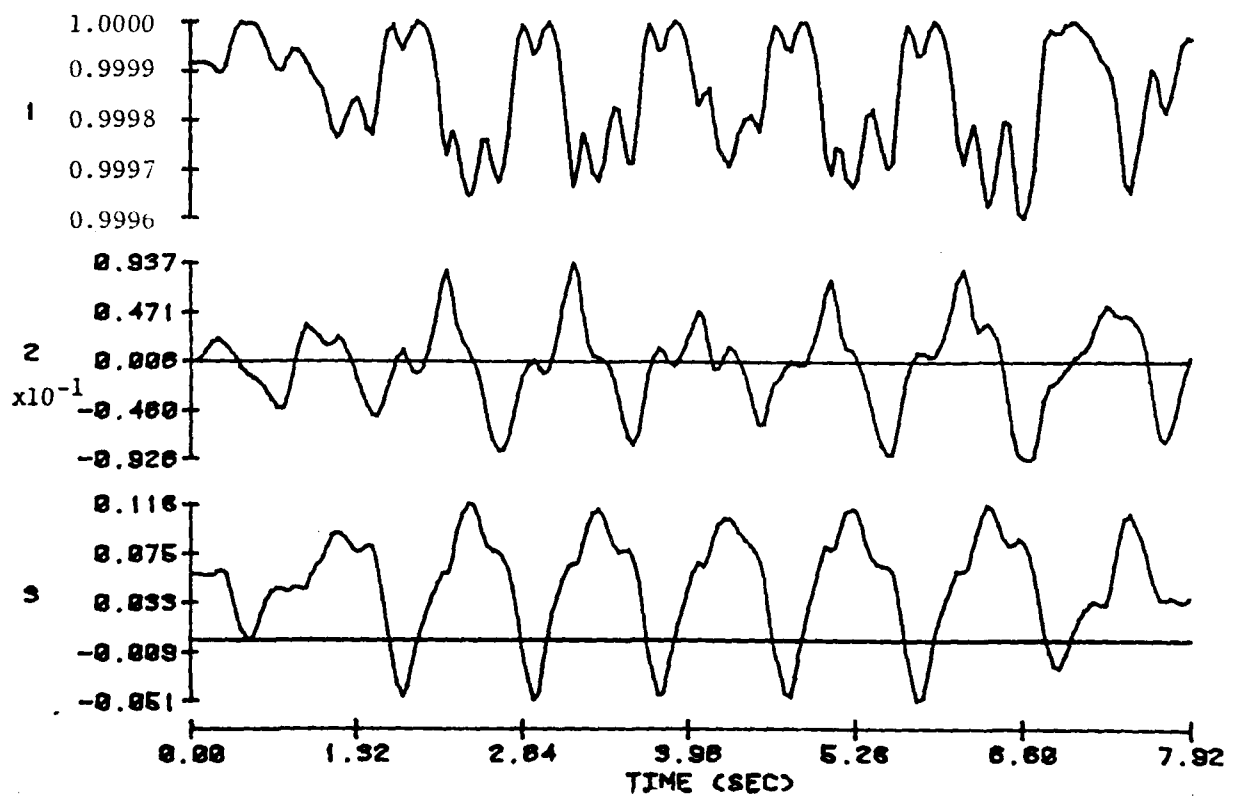
ANGLES THET, PHI, BET (deg)

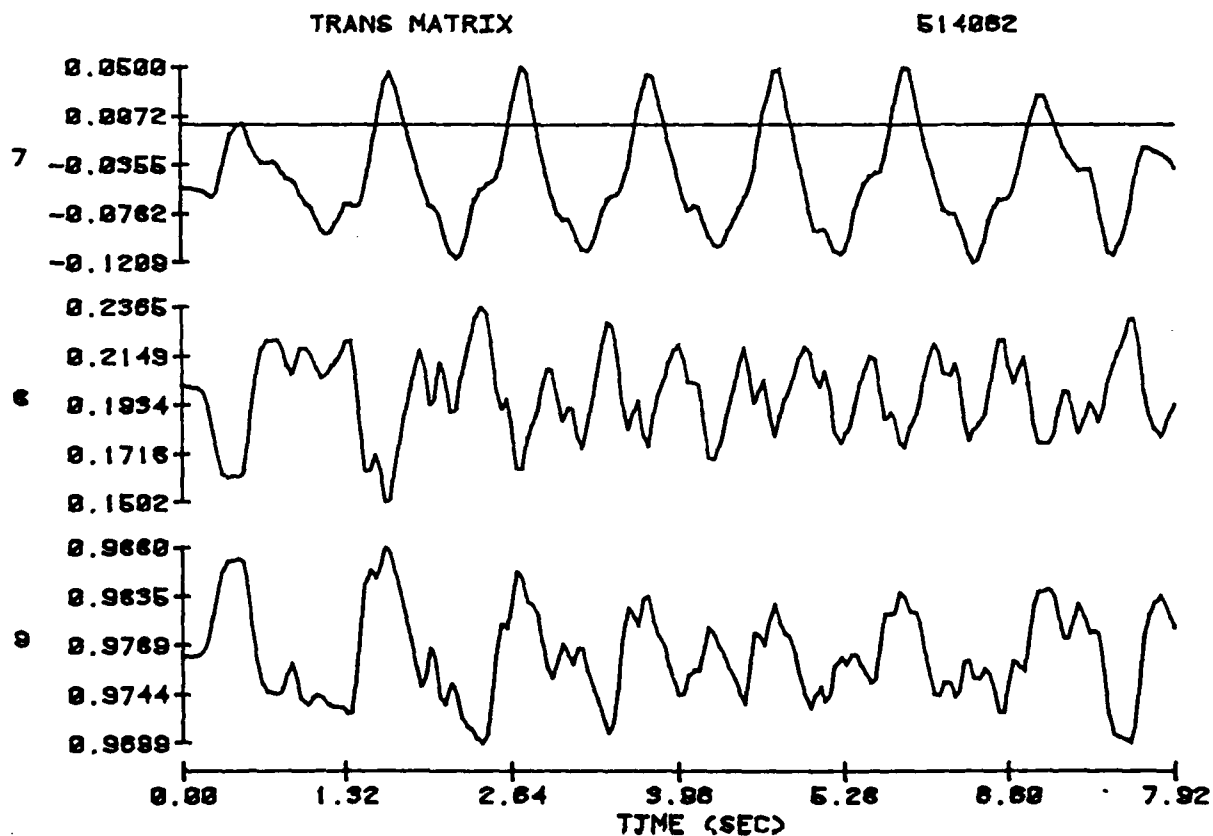
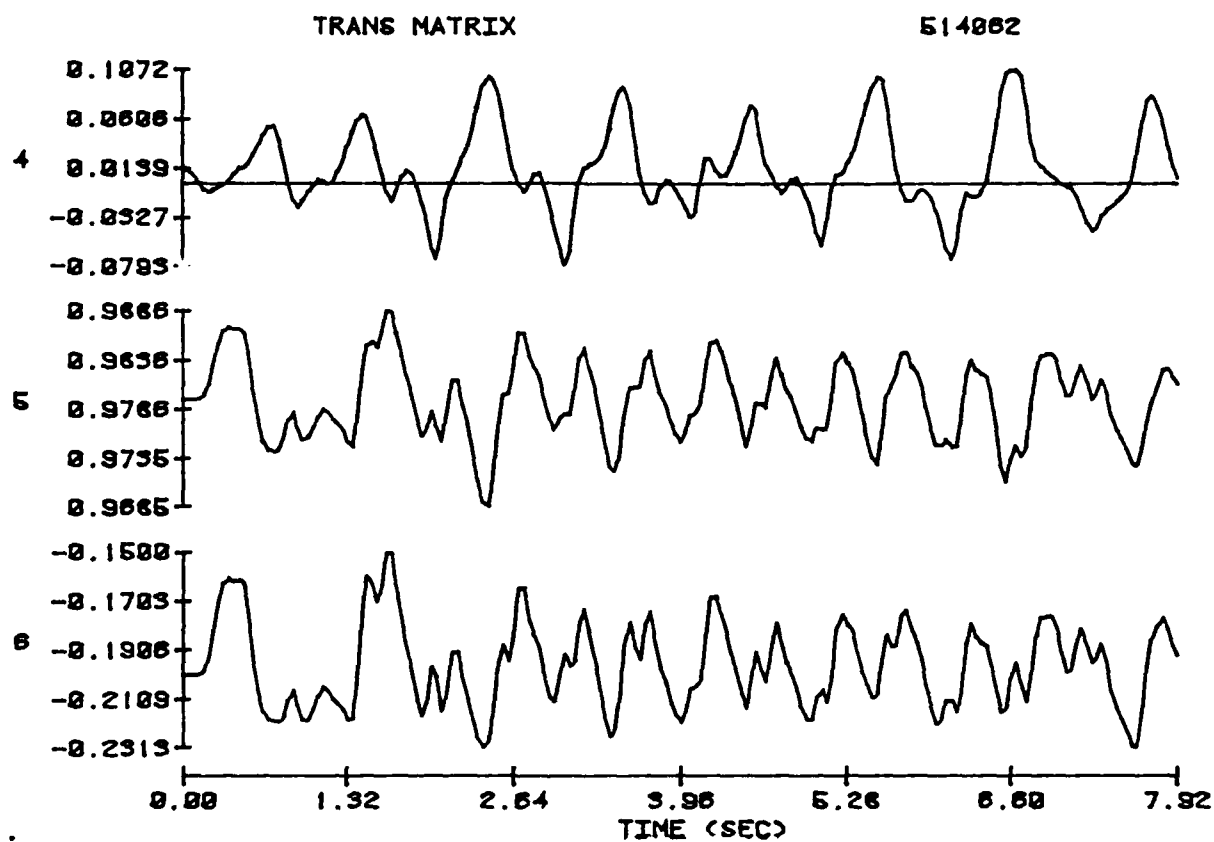
514062

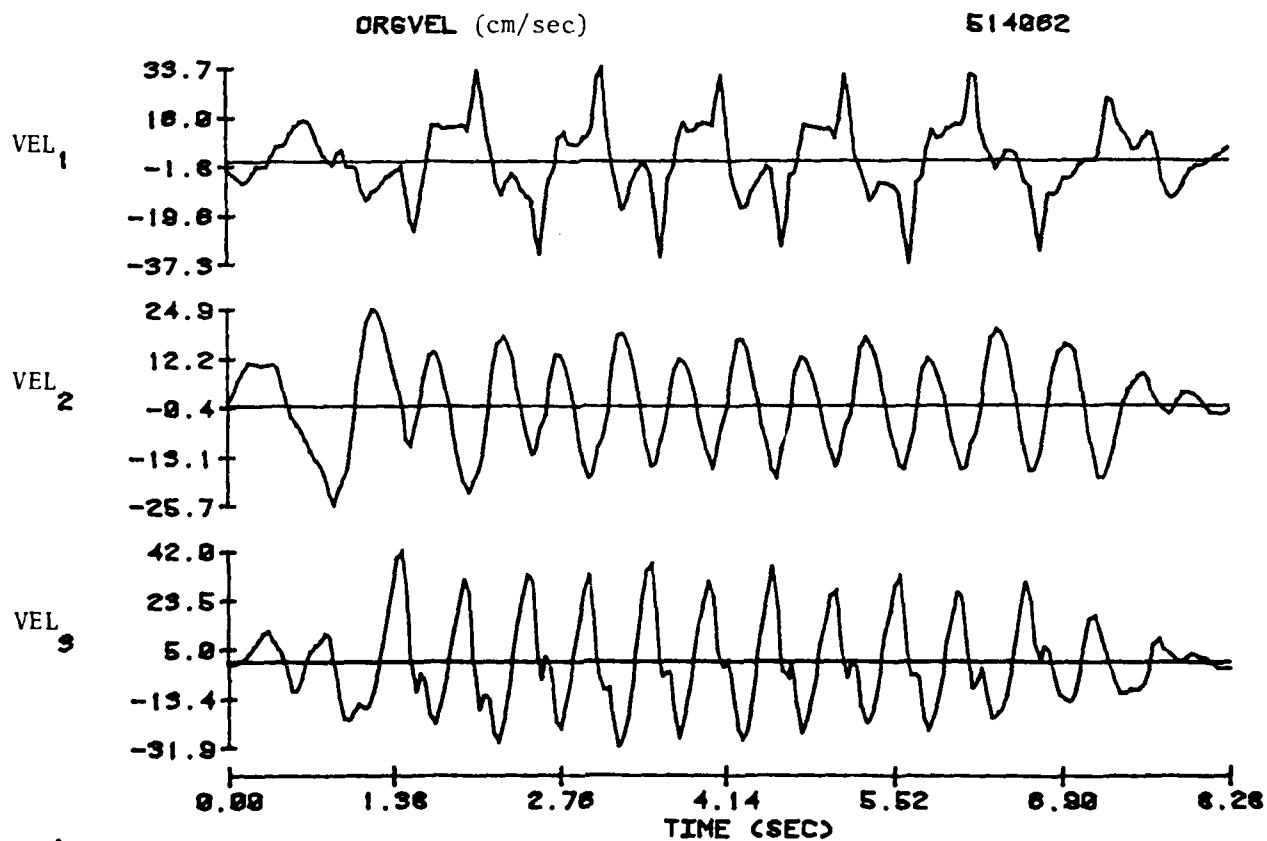
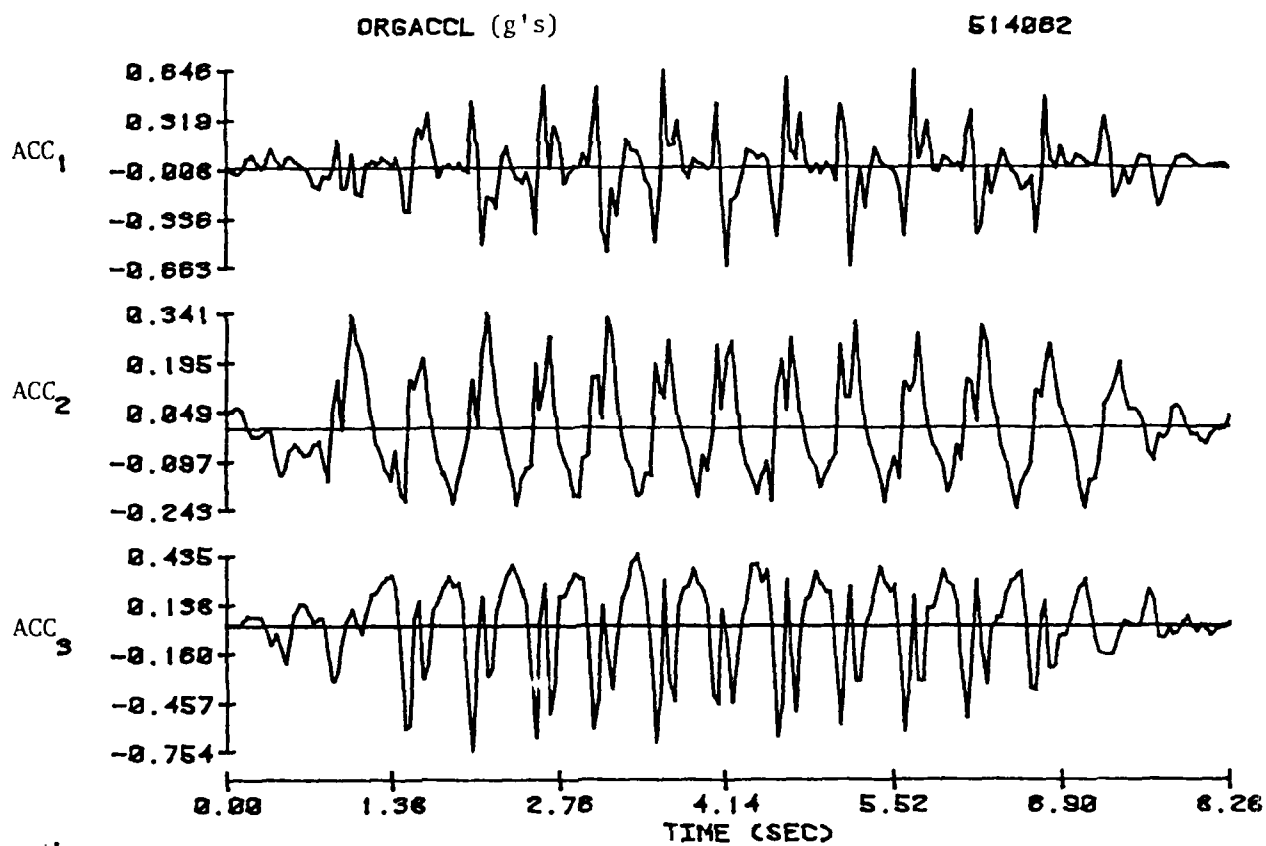


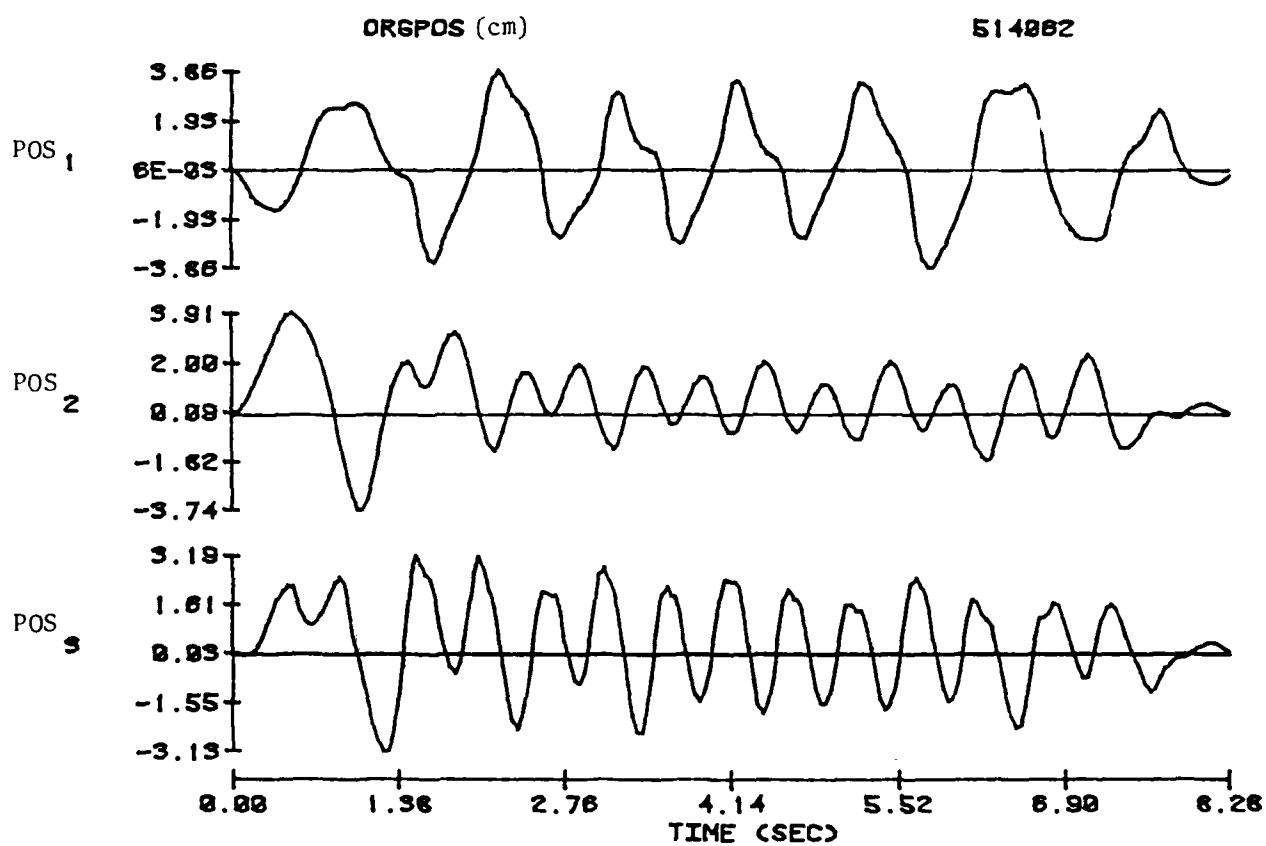
TRANS MATRIX

514062





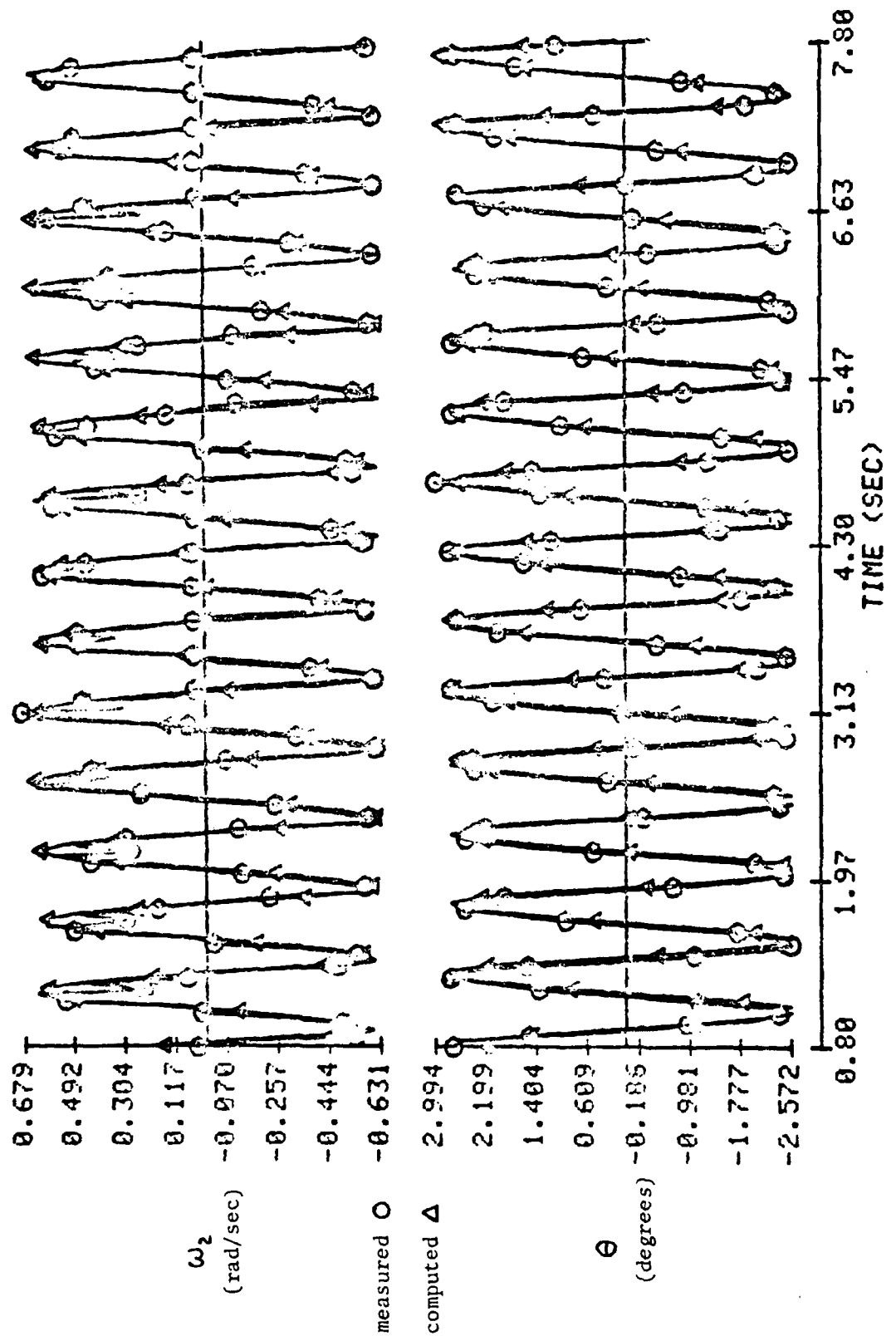




Plots of Experimental Tests

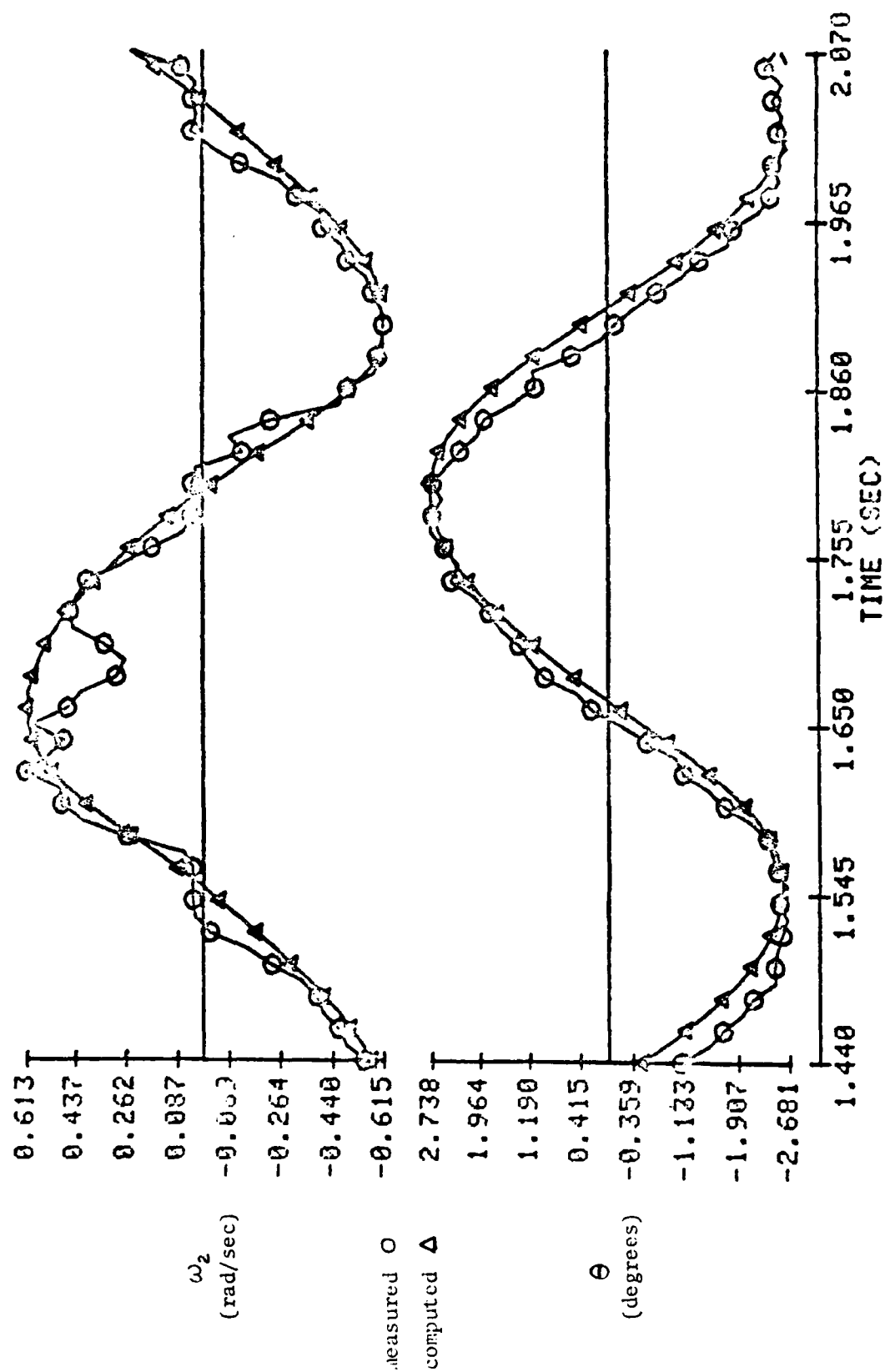
210998

HYD BENCH TEST



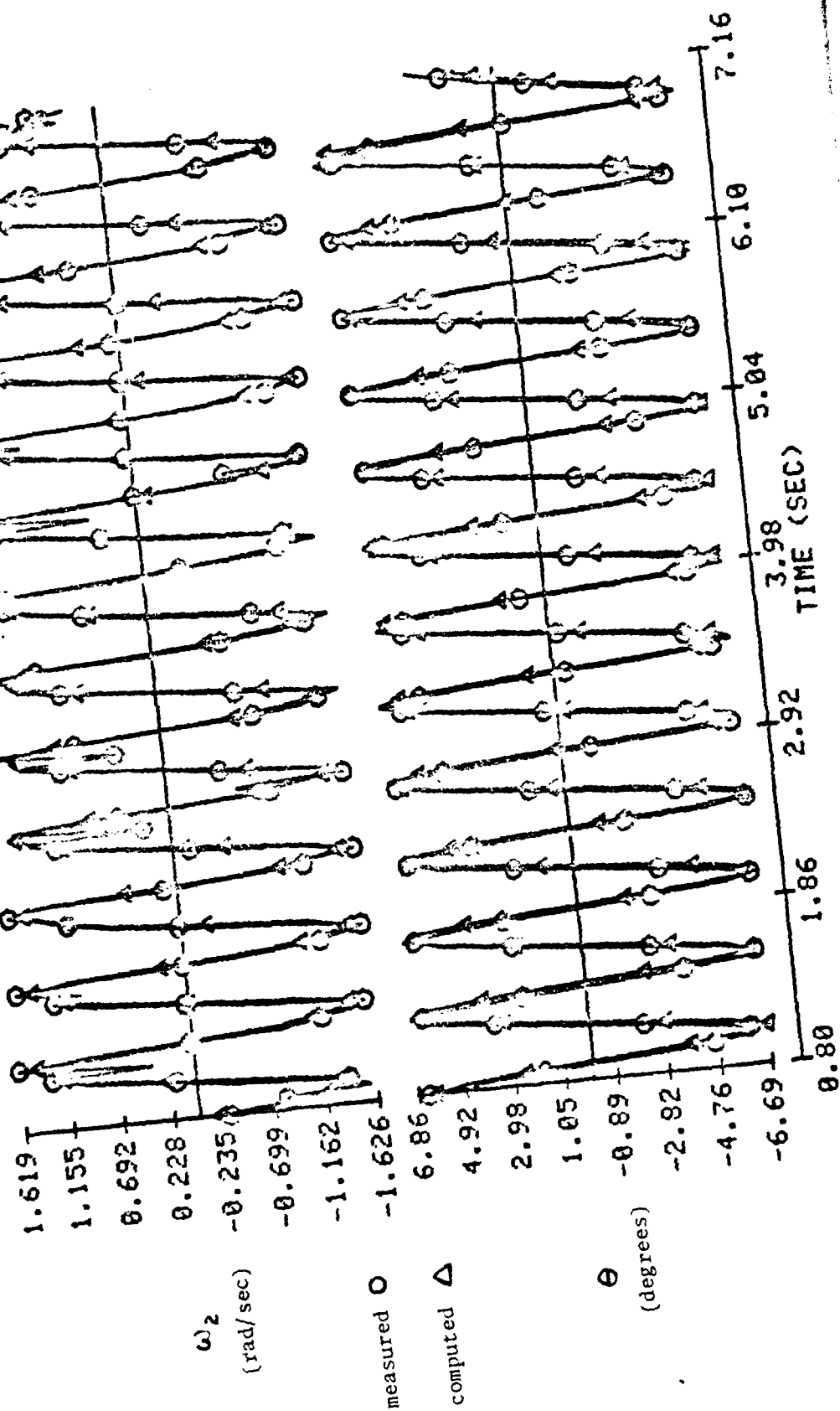
HYD BENCH TEST

210998

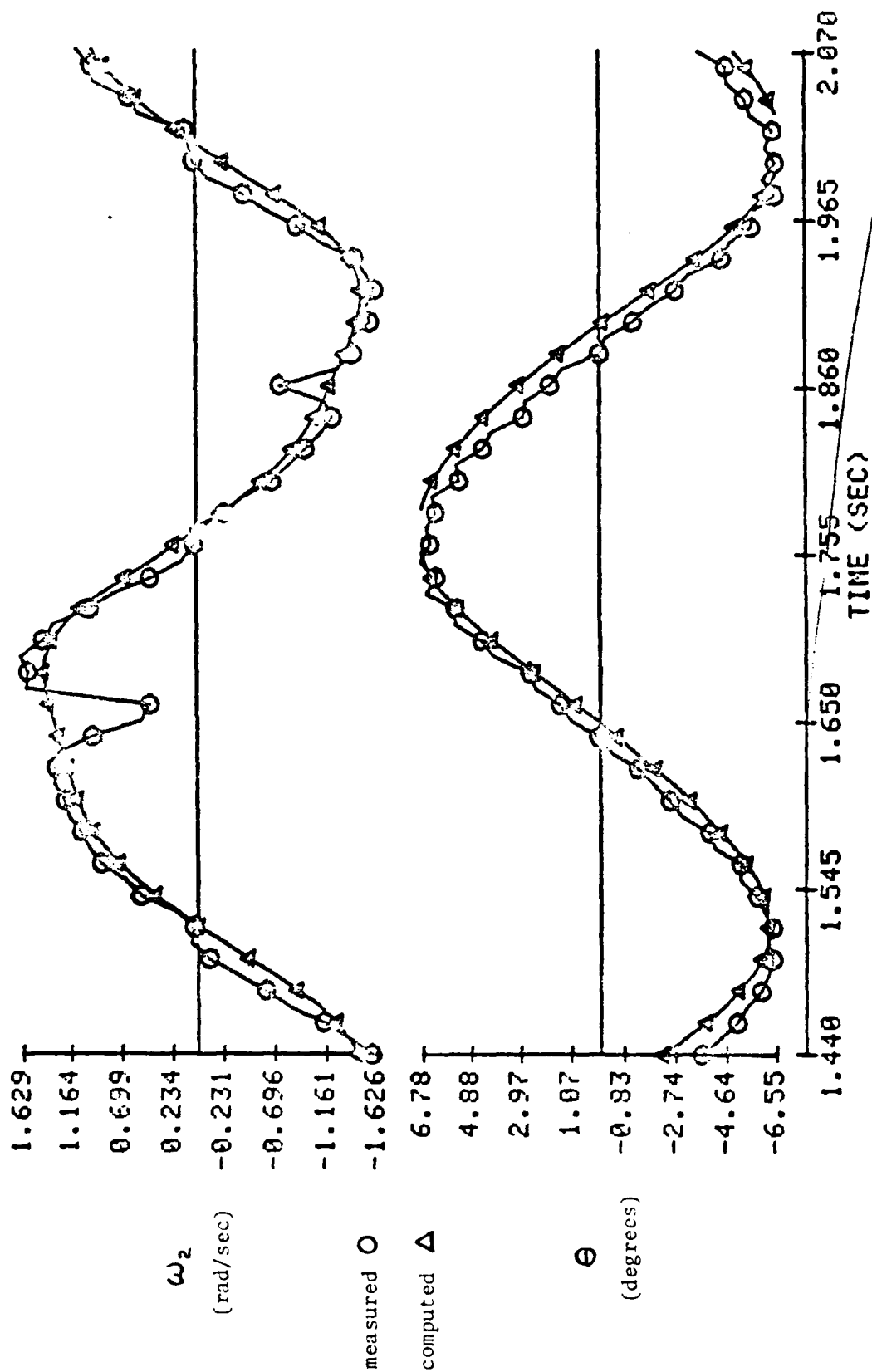


211998

HYD BENCH TEST



HYD BENCH TEST 211998



AD-A088 579

AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH F/G 6 16
THE DEVELOPMENT OF AN ACCELEROMETER SYSTEM FOR MEASURING PELVIC-- TC(U)
1979 D K MCMASTER
AFIT-79-209D

UNCLASSIFIED

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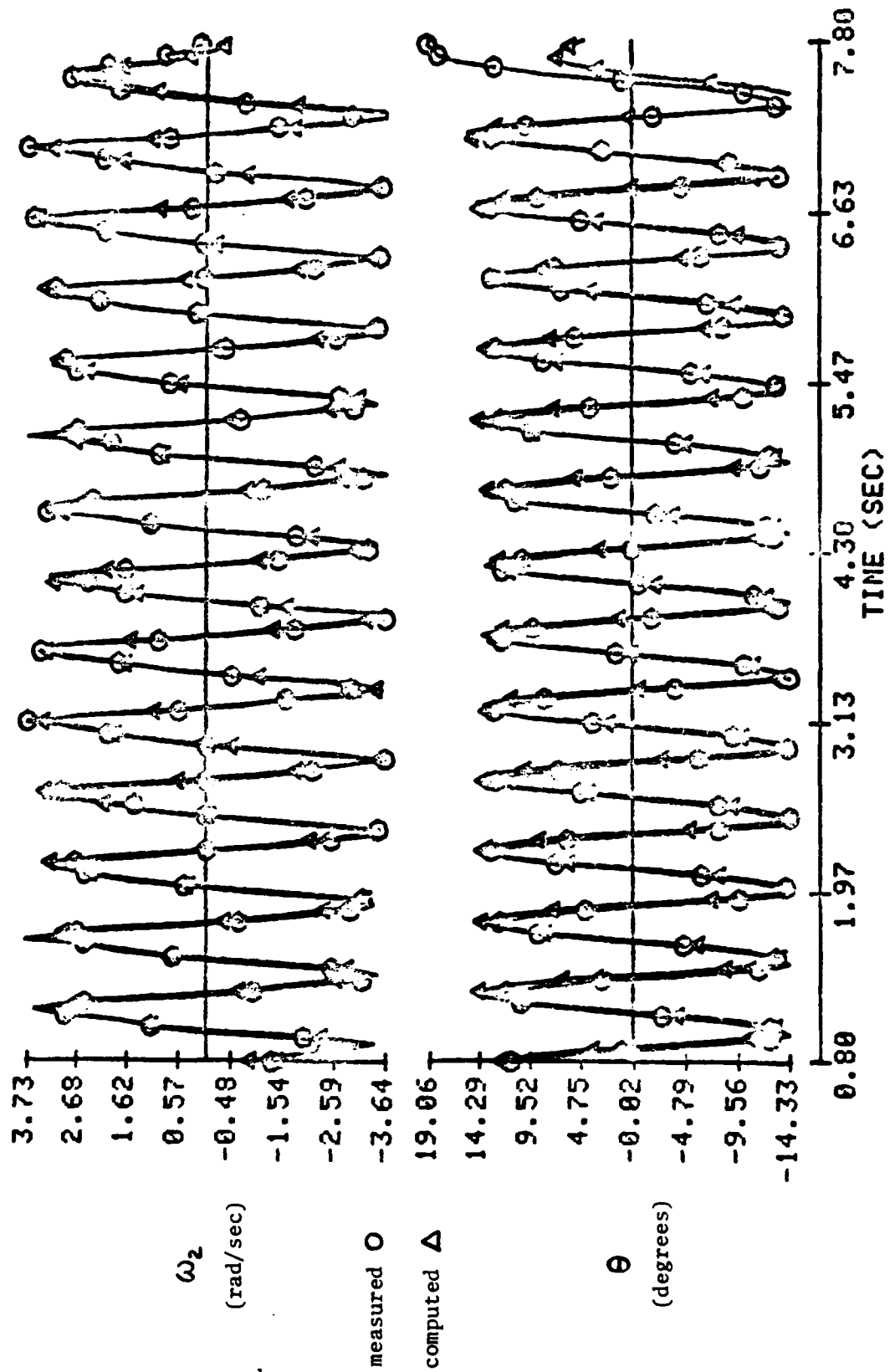
5 of 5
AD-A088 579



END
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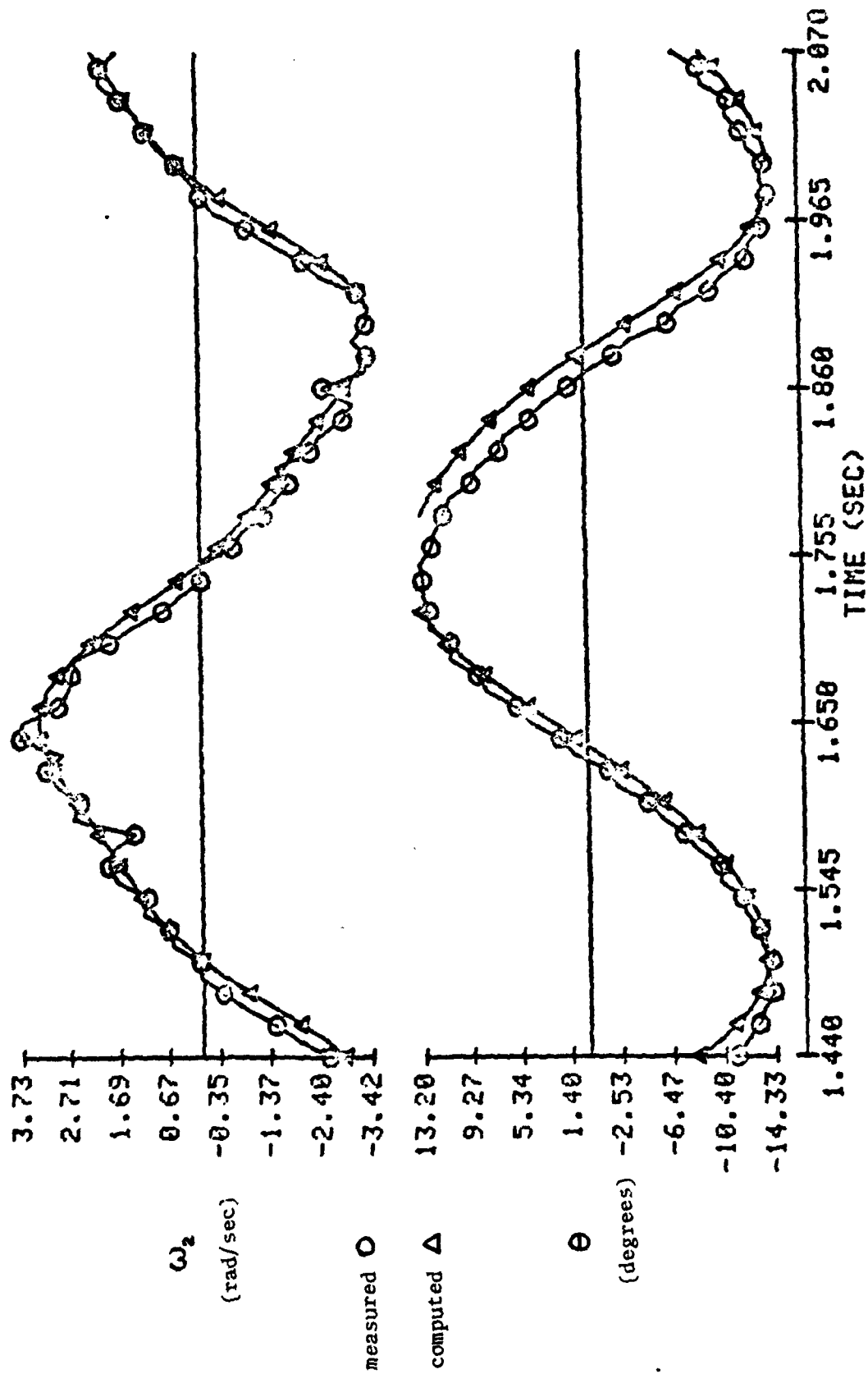
HYD BENCH TEST

212998



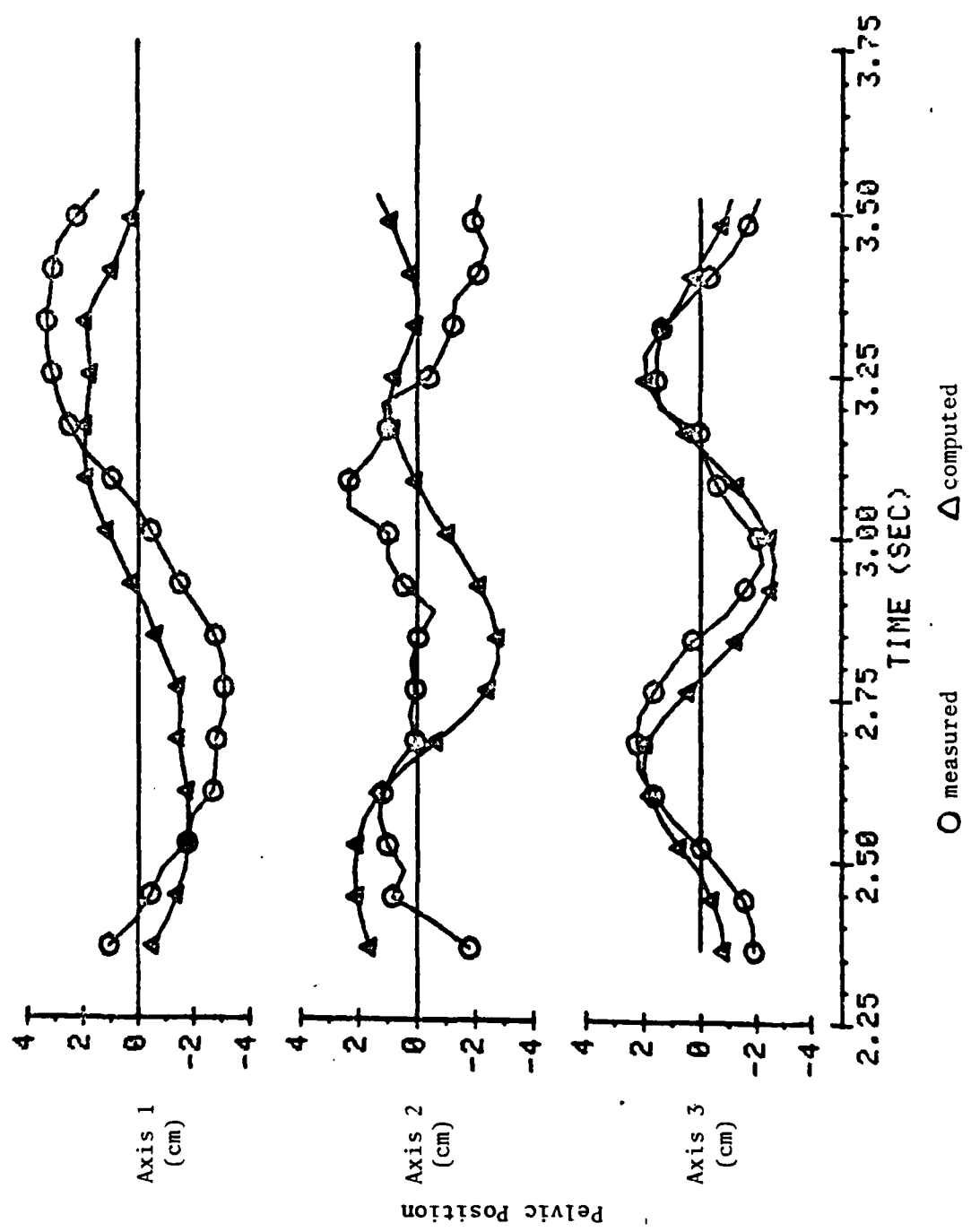
HYD BENCH TEST

212998



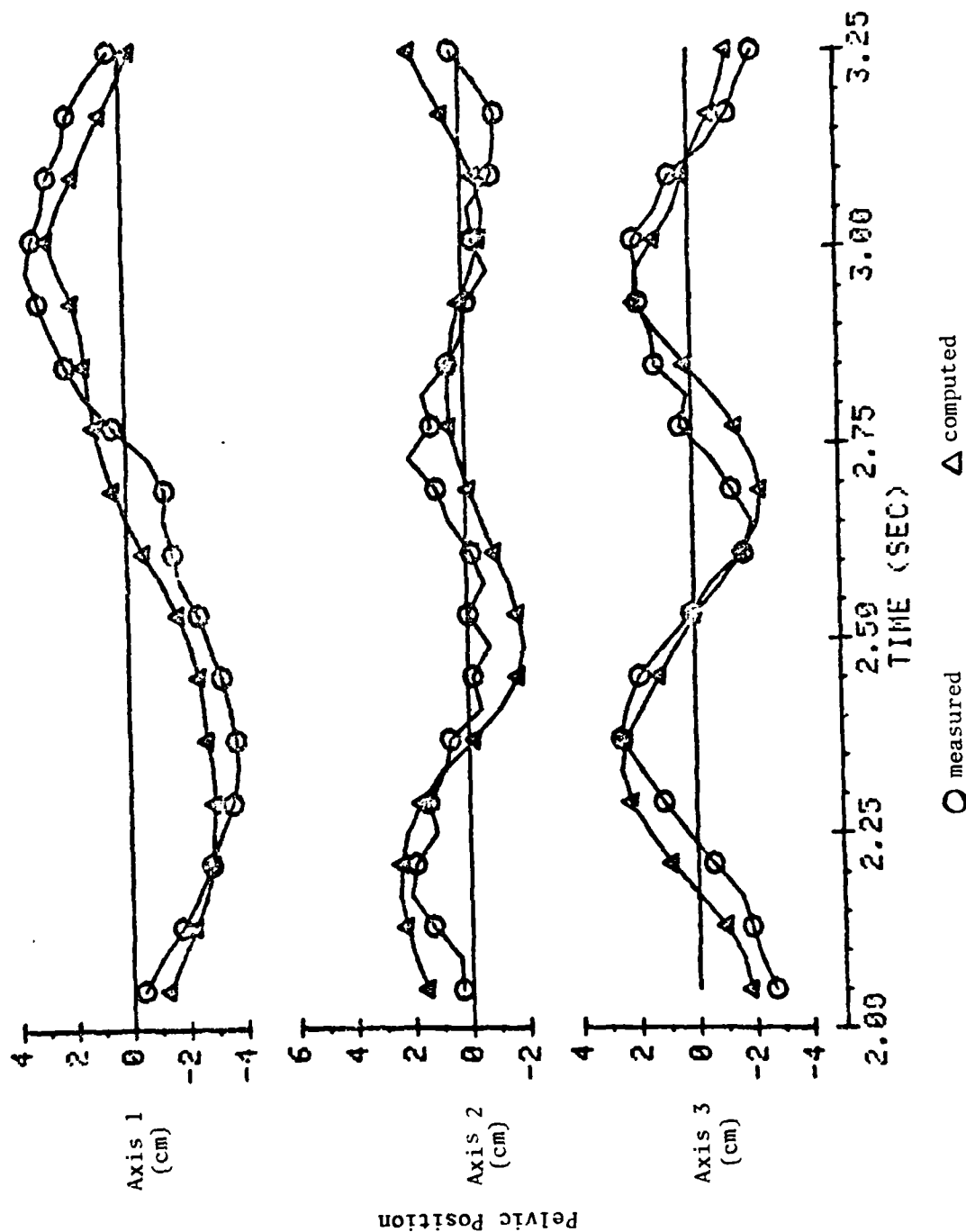
CIN203

CINE FILM PLOT



CIN204

CINE FILM PLOT



CIN207

CINE FILM PLOT

